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MULTIFREQUENCY EDDY CURRENT INSPECTION FOR CRACKS UNDER FASTENE--ETC(U)

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MULTIFREQUENCY EDDY CURRENT INSPECTION FOR CRACKS UNDER FASTENERS - PHASE II

G . H. Wilson, D. T. Hayford, and R. P. Meister

Battelle Columbus Laboratories
Columbus, Ohio 43201

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This report describes the second phase of a two-phase program. Phase I, reported in TR-76-209, was directed twoard the evaluation and demonstration of multiple frequency eddy-current (MFEC) using wing-splice samples and laboratory instrumentation to detect cracks under titanium and steel fasteners. This Phase II report covers the development evaluation of a prototype MFEC system for field use. The system was built around commercially available micro-computer modules coupled with in-house designed eddy current electronics,

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an eddy current probe, and a multifunction operator control panel. The system was "trained" using two C-5A wing panel sections having sawcuts to simulate cracks. Tenth-inch sawcuts at the top of the second layer could be repeatedly detected using a decision algorithm based on a combination of four frequencies. The prototype system was evaluated during July, 1978, as part of the C-5A Structural Evaluation and Inspection Program (SEIP). Of approximately 400 fasteners inspected with the system, one suspect was found and later confirmed with another NDE method. In continued development of the MFEC technique, methods must be investigated which will be tolerant of variations in geometry found around rib stiffeners and single fastener rows.

FORWORD

This report describes the second phase of a program conducted by Battelle's Columbus Laboratories to develop Digital Multifrequency Eddy Current System for detecting cracks under installed fasteners in aircraft structure. Phase I, reported in AFML-TR-76-209, was directed toward evaluation and demonstration of the MFEC technique. The objective of Phase II, reported herein, was the design, construction and preliminary field trials of a prototype field inspection system. The program was conducted in the Fabrication and Quality Assurance Section. Mr. R. P. Meister served as Program Manager. The program was performed under the technical direction of Mr. G. H. Wilson as Principal Investigator. Mr. D. T. Hayford was responsible for the eddy current procedure development and data analysis. Recognition is given to Mr. S. E. Kleszczelski for assistance in system fabrication and applications studies. The Air Force Project Monitors were Mr. Richard R. Rowand followed by Mr. J. Petru, AFML/LLP.

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SECTION I

SUMMARY

This report describes the second phase of a two-phase program for the development of multiple frequency eddy-current, MFEC, inspection for cracks under installed fasteners. Phase I was directed toward the evaluation and demonstration of MFEC using actual wing-splice samples and laboratory instrumentation to detect cracks under titanium and steel fasteners. A prototype MFEC system for field inspection of aircraft was constructed during Phase II and evaluated at Lockheed Georgia Company inspecting fasteners in wing splice joints of a C-5A under the SIEP program

The MFEC system was designed around a Digital Equipment Corporation LSI II microcomputer as a computing/controlling element with a floppy disk drive for data and program storage and a keyboard/printer console for communication between the operator and the system. In-house designed eddy current electronics, an eddy current probe, and a multifunction operator control panel complete the hardware components.

Inspection software, development software and hardware check-out software were developed. The inspection software provides the capability of (1) generating sinusoidal currents of various frequencies to energize the coil, (2) balancing the received signal from the inspection probe prior to an inspection sequence, and (3) making a multi-frequency eddy current reading on a fastener, doing real time processing on this reading by applying a crack/no crack decision algorithm and displaying or storing the results. The development software consists of various programs which were used while candidate crack/no crack algorithms were being developed and evaluated. The hardware check-out software is a group of programs used for the initial debugging of system electronics.

The system was "trained" using two C-5A wing panel sections having sawcuts to simulate 0.1, 0.2, and 0.3 inch cracks in the top of the second layer of a two-layer joint. These panels were the same ones used in Phase I, consisting of two 0.25-inch thick layers fastened with two rows of 1/4-inch diameter titanium

flathead fasteners. The sensitivity to cracks under titanium fasteners (0.3 inch minimum crack size) obtained in Phase I of the program using the cup core coil probe was insufficient to meet Air Force requirements. During this Phase II of the program, a differential probe coil was used which inspects only a segment of the circumference of the fastener hole to increase crack sensitivity. The final probe, designated DP2, consisted of two rectangular ferrite rods (1/4" X 1/2" X 1") having coil windings connected in a differential mode. The two poles of the probe are spaced 1/2 inches apart so that they rest on the aluminum panel equidistants from opposite sides of the fastener head.

Using the panels with known defects to train the system, a crack/no crack decision algorithm was developed using regression analysis. The general form of the decision algorithm is

$$C_L = \sum_{i=1}^{4} [A_i X_i + B_i Y_i + C_i X_i^2 + D_i Y_i^2 + E_i X_i Y_i] + K \qquad (1)$$

where C_L stands for crack estimator, X_1 through X_4 are the inphase measurements at four frequencies (95, 335, 1225, and 5000 Hz) and Y_1 through Y_4 are the quadrature measurements.

Using the developed system, the 1/10-inch saw cut at the top of the second layer in the joint could be repeatedly detected in the laboratory test panels. Use of the decision algorithm based on the combination of four frequencies was a better, more reliable predictor of defects than any of the four frequencies used alone.

The system was shipped to Lockheed Georgia Company, Marietta, Georgia, in mid July, 1978, for use on the SIEP inspection program. Lockheed technicians were trained to perform the tests. Approximately 400 fasteners were inspected using the system. One suspect was found which was confirmed using another NDE method.

Use of the system in the field trial was limited to inspecting joints of the same configuration as those of the laboratory test panels. Increases in panel thickness, such as at rib stiffeners, caused defect indications, thus these locations could not be tested. Joints having a single row instead of a double row of fasteners also could not be tested using the developed test probe.

To continue this development, methods must be investigated which would be more tolerant of these variations in geometry.

SECTION II

INTRODUCTION

1. PROBLEM AND PROGRAM GENESIS

Fatigue cracks propagating from fastener holes in multilayered, fastened members is a problem common to many aircraft structures. Stress levels in interior structural layers of a mechanically fastened joint can equal or exceed the stress levels in the exterior layer. Therefore, there is a high probability that primary crack initiation and growth can occur in interior layers. These cracks usually initiate at the faying surface between joined plates and propagate in a radial direction from the fastener hole.

A nondestructive test that can detect cracks in interior layers is highly desirable because removal of fasteners for inspection is costly. Fastener nuts are not readily accessible and fastener bolts are difficult to remove without damaging the hole. Holes usually have to be resized and finished after the fasteners are removed. Substantial savings in the costs of unnecessarily removing fasteners can be realized if a fastener hole can be inspected with the fastener in place. Since aircraft such as the C-5A can have hundreds of critical fastener holes that require inspection, the savings provided by a reliable inspection technique is considerable.

Inspection by X-rays is difficult and costly. Radiography lacks sensitivity and definition in many cases where structures are complex. Ultrasonic techniques are essentially limited to the exterior layer only and, therefore, provide less than adequate inspection.

The C-5A SPO funded Lockheed-Georgia to contact those organizations knowledgeable about nondestructive techniques that might be used for detecting cracks under fasteners in multilayered aluminum structures. The MFEC technique developed by Battelle-Columbus appeared to have the greatest potential for success. Under a C-5A SPO funded Contract (No. F33657-73-C-0281), it was found that with MFEC we had the potential of detecting 0.125-inch radial length cracks 0.4 inch below the surface with fasteners installed. Since this potential detection capability could satisfy many inspection requirement on aircraft structures, such as the B-52, KC-135, and F-5, as well as the C-5A, successful development of the

MFEC technique offered promise of tremendous cost savings warranting continuing the development of the technique under Air Force sponsorship.

2. MULTIPLE FREQUENCY EDDY CURRENT

The MFEC technique, like other eddy-current techniques, offers several capabilities that are desirable for inspection for cracks under fasteners. In general, the eddy-current techniques are fast and require no coupling media between test coil and inspection piece. However, standard commercial eddy-current devices do not appear to be good candidates for detecting cracks under fasteners, because (1) the cracks are subsurface and eddy-current testing is penetration limited, and (2) the eddy-current signal response is highly influenced by variables associated with the fastener and sheet material.

MFEC involves the simultaneous or rapid sequential energization of the eddy-current test coil with a number of sinusoidal current wave-forms, each having a different frequency. The test-coil response signals associated with each frequency are then detected, and combined to provide a composite signal that is a measure of the variable of interest, in this case, the crack under the fastener. The responses of the eddy-current test coil to the different variables changes with a change in the excitation current frequency. It is possible to take advantage of these changes in response at different frequencies to sort out the responses produced by the variables of interest from the response of all the other variables. In this way, the variable of interest produces a maximized response, while the response of the unwanted variables is minimized; the composite signal is influenced to a minimum extent by minor variations in fastener fit, metallurgical variations in the fastener or aluminum sheet, joint geometry variation, and test-coil position with respect to the fastener center.

3. PHASE I STUDIES

At the conclusion of the preliminary studies carried out under the C5A SPO Contract, Battelle proposed a program to develop a prototype MFEC system for detecting cracks under fasteners in layered aircraft structures. This program consisted of two phases. Phase I was to be directed at optimizing the techniques and procedures required to detect simulated cracks (machined notches) in fastener

holes, as small as 0.1 inch in radial length in the second layer of an equithickness two layer joint 0.4 inches thick. Phase II was to be directed at design, construction, and evaluation of the prototype MFEC inspection system defined by Phase I.

In December, 1975, the Air Force authorized the start of the work in Phase I. Specific objectives were to:

- o Develop improved test coils
- o Develop improved signal generation and balancing techniques
- o Optimize data analysis procedures for evaluating MFEC output.

The work carried out and results obtained in Phase I were reported in AFML-TR-76-209 dated December, 1976.

Evolving from this Phase I investigation was the concept and bread-board demonstration of a digital eddy-current system that provides a stable acquisition of eddy-current response signals, more reliable detection of cracks and a versatile automatic control of the inspection process.

A major conclusion from that study was the digital MFEC has the potential for detecting 0.3-inch and 0.1-inch cracks under titanium and steel fasteners respectively in the bottom layer of two-layer aluminum joints 3/8 to 1/2 inch total thickness. Although the sensitivity to cracks under steel fasteners was satisfactory, the sensitivity to cracks under titanium fasteners was not satisfactory. The Air Force objective is to detect cracks 0.1 inch long and smaller if possible. This would greatly facilitate repair of the fastener hole by drilling it oversize and installing a larger diameter fastener.

Upon review of the Phase I program, it was decided, that a major improvement was needed to enhance sensitivity to cracks around titanium fasteners. The observation had been made that cracks around fasteners almost always initiate on the side of the fastener nearest the edge of the joint and propagate toward the joint edge. Generally, at some later time a crack will initiate on the opposite side of the fastener and propagate into the sheet. Based on this observation, it was decided that if higher crack sensitivity could be obtained by limiting inspection to a segment of the fastener hole circumference, the segment adjacent to the edge, this would still be a very viable inspection technique. Other segments around the fastener could be inspected using the same technique, however, several separate inspections would be necessary to inspect the full circumference of the fastener hole.

A brief one-month study was funded to evalute a side coil, designed to interrogate only the segment of the fastener circumference near the joint edge. In the Phase I study, a cup-core eddy current coil which inspects the full circumference of the fastener hole had been used. The side coil study program was designed to obtain comparable data to that previously obtained with the cup-core coil so that conclusions could be made regarding defect senstivities attainable with each.

It was found the use of a side coil, inspecting one segment of the fastener hole, provides greatly improved crack sensitivity over cup core coil, full hole circumference tests for cracks around titanium fasteners. The side coil exhibited excellent potential for developing a technique to detect 0.1 inch cracks in the second layer of 0.5 inch thick joints.

4. PHASE II OBJECTIVES

Based on the results of Phase I and the promising results obtained in the side coil evaluation, Phase II of this contract was initiated in April, 1977, with the objectives

- o Design and construct a prototype MFEC system suitable for field use by depot personnel for inspection for cracks under fasteners on actual aircraft sturucture.
- o Evaluation of the system on various samples to further define system capabilities and operating procedures.
- o Train and support Lockheed personnel in field trials of the system on a C-5A aircraft.

It was not the intent of this program to produce a field-ready system but, as far as possible, a field usable system so that field experience could be obtained.

SECTION III

SYSTEM DESIGN AND FABRICATION

I. DESIGN CONSIDERATIONS

The principle design objective of the Phase II program was to transfer the essential elements of the Phase I MFEC system into a package suitable for field use. Additionally, any appropriate enhancements or system improvements were to be included in the Phase II system. The requirements mandated by this objective are outlined below:

- o Generate multiple frequencies suquentially,
- o Excite eddy current probe and measure voltage of the returned signal,
- o User oriented system command and control,
- o Implement sophisticated real time data processing,
- o System packaging suitable for field evaluation,
- o Delivery of system components within 3 months

Consideration of these requirement led to the selection of (1) Digital Equipment Corporation's LSI II microcomputer as a computing/controlling element, (2) a floppy disk drive for data and program storage, (3) in-house designed eddy current electronics, and (4) a multifunction operator control panel. The elements were combined to produce a MFEC system with one-fifth the size of the Phase I system and several performance improvements.

The LSI II was chosen for several reasons: First, the extensive software support and architectural similarity to the PDP II/40 system used during Phase I helped to cut development time. Also, the LSI II is compact in size, available off the shelf through several sources, and has steadily gained in popularity with industry and government users. Its slower execution time (approximately one-fourth that of the PDP II/40) would impact only the system's upper frequency limit since the LSI II has adequate execution speed for the real time data processing requirements of the MFEC system.

By designing dedicated circuits for generating the excitation frequencies, the upper frequency limit was raised an order of magnitude from 2000 Hz to 20,000 Hz. Had the Phase I method for frequency generation been used, the upper limit would have been cut from the marginal 2000 Hz to an unacceptable 500 Hz due to the LSI II's slower execution speed.

The selection of floppy disks for program and data storage provided adequate bulkstorage in a package smaller than that used by Phase I removable cartridge disks. Also, the floppy disks are a compact 8-inch by 8-inch size and may be stored in a 3-ring note book.

The emphasis on user oriented system command and control was accommodated by adding a remote control panel for operator interaction during routine inspection and by carefully designing the software written for Phase II.

The framework developed for the software was designed by balancing two conflicting requirements: (1) simple operation for routine, repetitive inspection and (2) great flexibility for acquiring and processing MFEC data for further research and development in this area. These two requirements were both accommodated by developing a family of programs, some for routine operation, others for sophisticated data processing. Many of these programs contain options which are selected at run time. These options are chosen by the operator entering either a numerical option code or a mnemonic command to the program.

2. HARDWARE COMPONENTS

This section and the next contain a description and general information about the MFEC system's hardware and software respectively. Further details such as hardware schematics and software listing are contained in the Operating and Service Information document provided with the system.

Hardware for the MFEC System (Figure 1) consists of a console atop a cabinet which houses the system's electronics, a remote operator's panel, and the inspection probe. The block diagram of Figure 2 depicts the functional relationship of the system's components to each other.

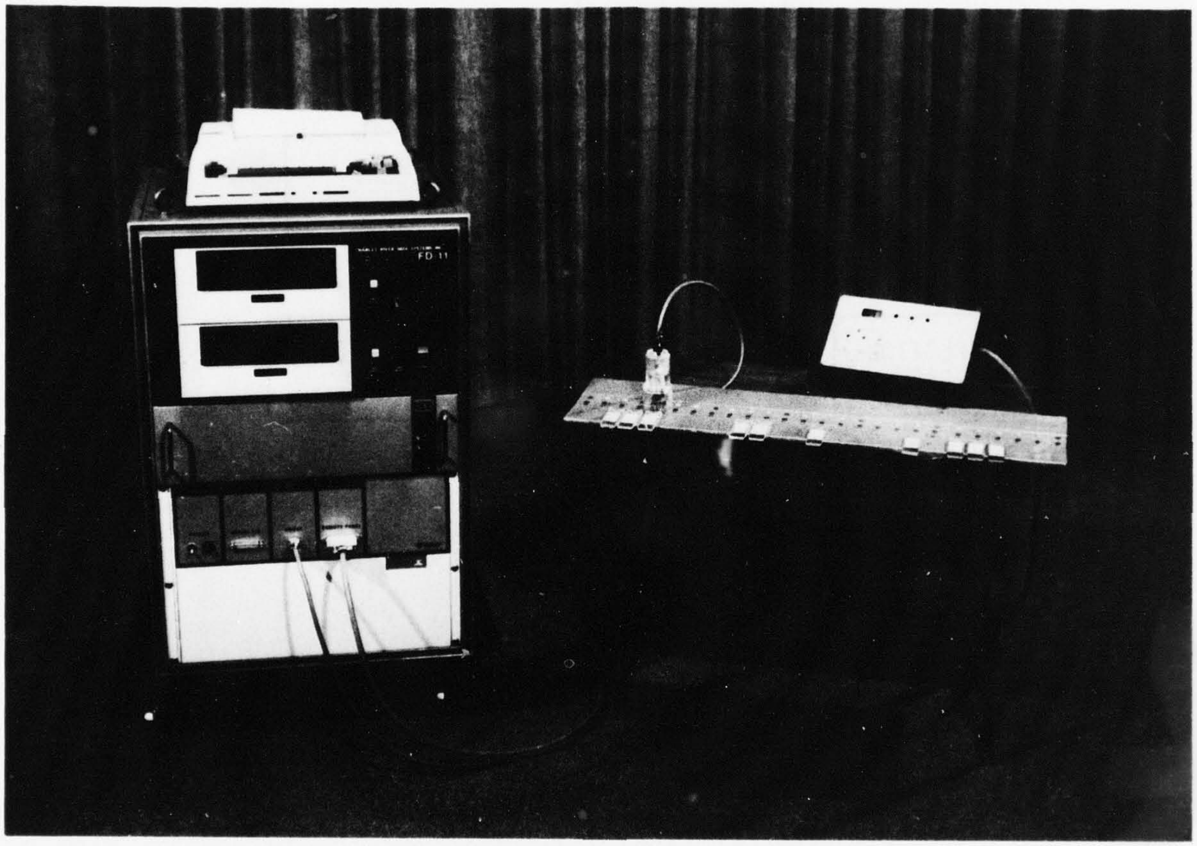


FIGURE 1. DIGITAL MFEC SYSTEM

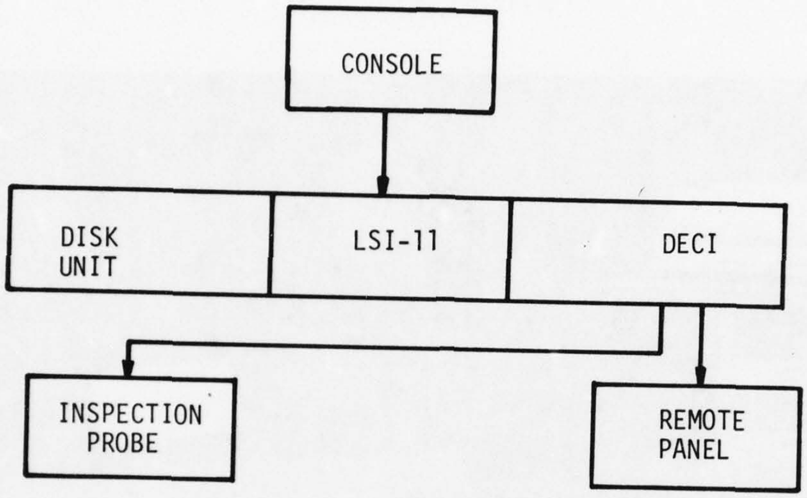


FIGURE 2. HARDWARE BLOCK DIAGRAM

The console is a keyboard and printer unit used for general communication between operator and the system. Commands related to fastener inspection and data processing are entered on the console keyboard while the printer serves as a listing device for inspection results and other data.

The floppy disk unit, LSI II computer, Digital Eddy Current Interface (DECI), and associated power supplies are all housed in the 21 x 21 x 30 -inch cabinet. This cabinet is cooled by two fans which circulate filtered air through the system and it is mounted on four rubber tires for mobility. System power requirements are 110 VAC, 5 amps.

The upper portion of the cabinet is filled by the floppy disk unit which contains two drives. During inspection procedures, a disk containing programs for data acquisition and data processing is placed in the top drive; while a disk in the lower drive is used for storing MFEC data. The floppy disk unit is also used during software development. In this application the disks are used to store programs in source format and to permit running software development tools such as a text editor, a macro assembler, a FORTRAN compiler, etc. When operated in this manner, the MFEC system can be used to create and make changes in the MFEC data acquisition and processing software. This feature permitted useful changes in operating procedures to be made in the field during the system's field evaluation. As an example, it was found that the repetitive specification of option codes and computer file names was the cause of most of the errors made by inspection personnel. Several simple changes in the software eliminated the need for most of the input by less experienced personnel, while keeping the original flexibility for more experienced personnel.

The LSI II computer is housed in the MFEC cabinet below the disk unit. This general purpose 16-bit computer is configured with 30K words of memory and these interfaces: an interface for the dual disk unit, a serial interface for the console, a spare serial interface used for a high speed console or modem, and a parallel interface for the DECI. The computer provides a vehicle through which the MFEC system may be programmed for data acquisition, data processing and system control. It is this programability that gives the MFEC system the flexibility needed for initial system development and continuing system improvements.

The Digital Eddy Current Interface is a hardware device which gives the MFEC system its eddy current capabilities (i.e., the ability to excite a driver coil and measure the induced voltage across a pickup coil). The DECI also provides a link to the remote operators panel. It is built on eight 4.5 by 9.6 -inch circuit cards mounted in a card rack located directly below the LSI II. These cards were designed specifically for this project and were assembled primarily by wire wrapping with some solder connections.

The remaining pieces of the MFEC system are the inspection probe and the remote panel. These two items are connected to the system by 20-foot cables, and therefore may be carried to the fastener to be inspected. Details of the probe are covered in other sections of this report; however, from a system standpoint, the probe consists of a driver coil circuit and two pickup coils which are connected to the system through the DECI. The remote-panel serves as a means of communication between the operator and the system during a routine fastener inspection sequence. The panel contains buttons and switches for operator input to the system. For system output to the operator there are lights, an audible beeper, and a 3-digit display.

3. SOFTWARE PROGRAMMING

All software used on the MFEC was developed with and runs under Digital Equipment Corporations RT II real time operating system. FORTRAN was used for all programming tasks except those dealing directly with the DECI. For the case of communicating with DECI hardware, FORTRAN callable subroutines were written in assembly language. The family of programs used for the MFEC system may be divided into three catagories: inspection software, development software, and hardware check-out software. The first two catagories will be discussed now; the third, along with additional information about the first two, is covered in the Operating and Service Information document.

A. Inspection Software. As depicted in Figure 3, the inspection software consists of two programs and three types of data files. The TSTBAL (test balance) program is responsible for balancing (nulling) the received signal from the

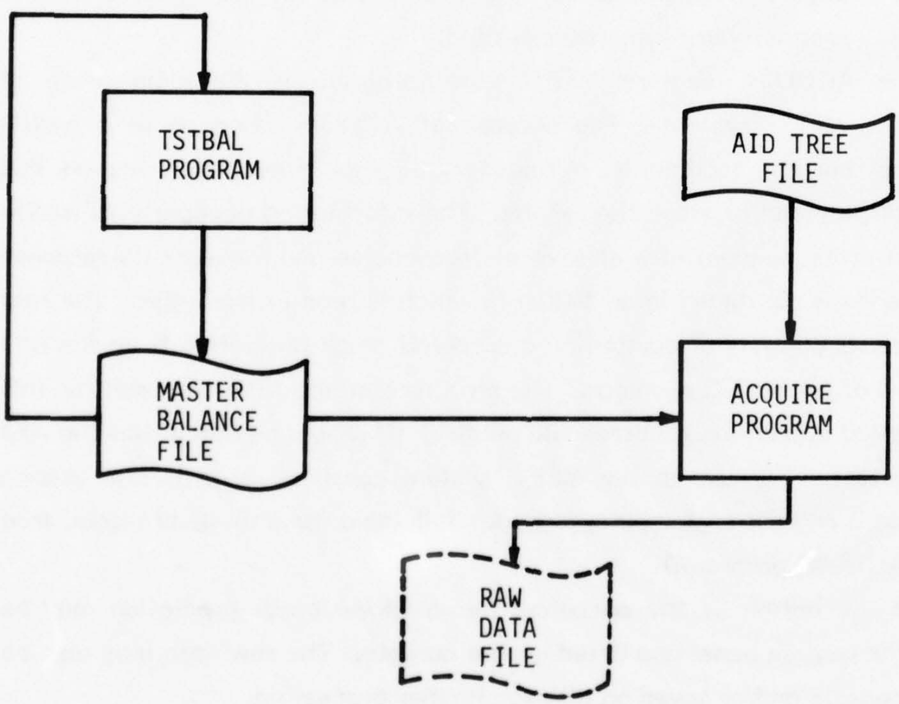


FIGURE 3. INSPECTION SOFTWARE

inspection probe prior to an inspection sequence. This nulling is used to remove fluctuations (due primarily to temperature variations) in the electronics and inspection probe. Since it is desirable to save the balance condition from day to day, and the LSI II uses volatile memory, this information is stored in an MBL (master balance) file on disk. The MBL file contains not only balance conditions, but also other information such as amplifier gains and timing counts needed to run the DECI.

The method used by TSTBAL for balancing is a three step operation:

(1) Read in the contents of a previous MBL file from disk.

(2) Systematically vary the amplitude and phase of a compensating balancing signal until it nulls out the signal received from the inspection probe which has been placed in air.

(3) Save the new, updated MBL file on disk for use by the ACQUIR program during fastener testing.

The ACQUIR (acquire MFEC data) program is the main piece of software in the MFEC system. The purpose of ACQUIR is to make a multi-frequency eddy current reading on a fastener, do real time processing on this reading, and display and/or store the results. The information necessary to excite the inspection probe sequentially at several frequencies and measure its response at each frequency is contained in an MBL file which is read in from disk. The real time data analysis consists of computing a crack/no crack prediction from the AID tree processing of the MFEC readings. The structure of the AID tree used for this processing is read in from an AID tree file on disk. (It should be noted that the AID tree finally selected for use in the MFEC system consisted of only one branch (split) based on a regression formula; but that full logic for a multi-branched tree exists in the ACQUIR program.)

At the option of the operator, the crack/no crack prediction may be displayed on the remote panel and listed on the console. The raw data may also be listed on the console and/or saved on disk for further processing.

B. Development Software. Of the family of programs developed for the MFEC system, several fall into a class labeled Development Software. These programs were used while candidate crack/no crack algorithms were being developed and evaluated. The functional relationship between these programs and various types of data files is indicated in Figure 4 and described below.

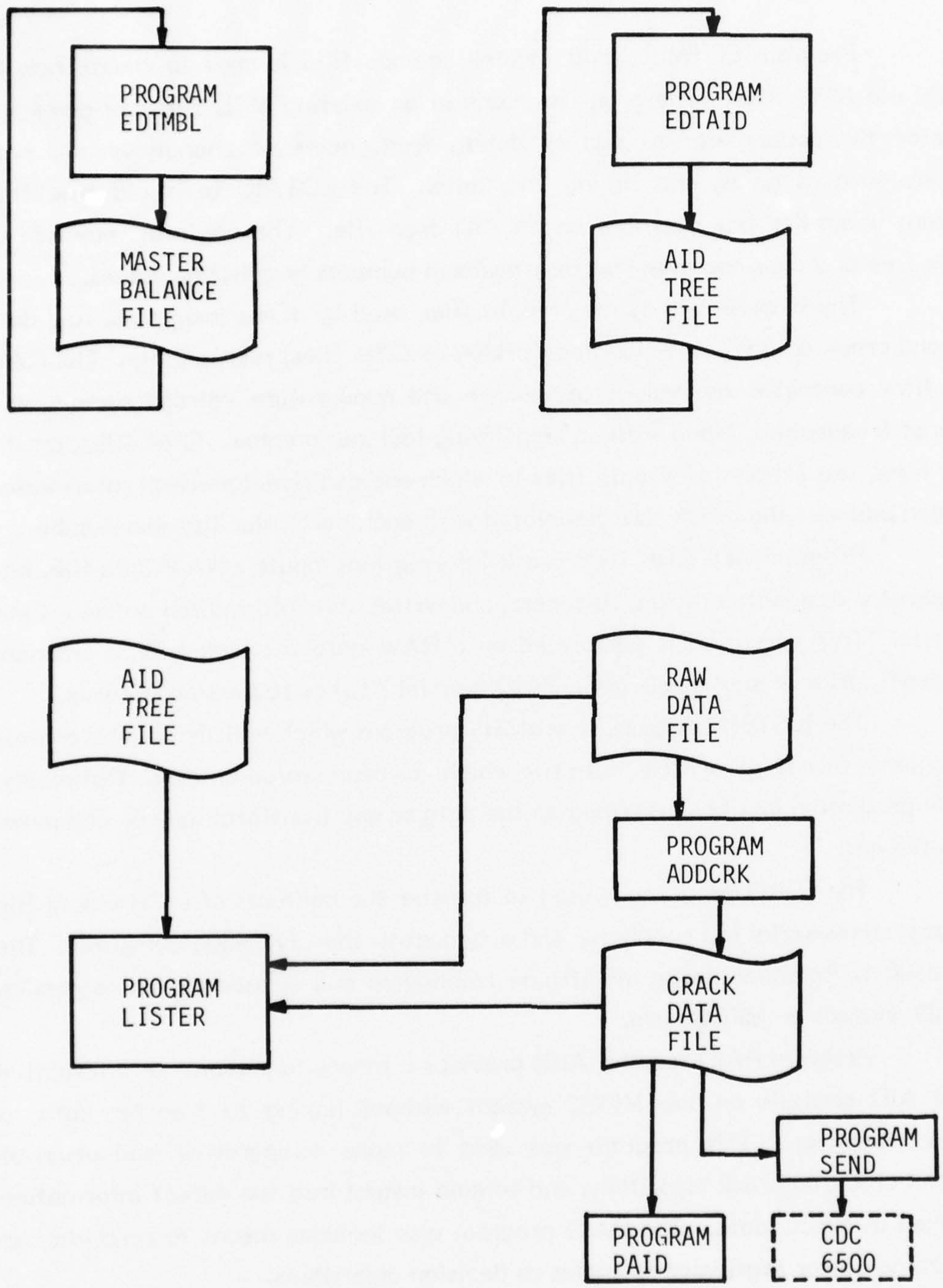


FIGURE 4. DEVELOPMENT SOFTWARE

Program EDTMBL (edit master balance file) is used to create new or modify old MBL files. The program reads in an existing MBL file and gives the operator the opportunity to add or delete frequencies or change various parameters such as gains, and timing constants. The EDTAID (edit aid tree file) program is similar but operates on an AID tree file. The operator may add or delete tree branches and may change transform numbers or splitting values.

There were two types of data files used by these programs, raw data files and crack data files, designated as RAW or CRK files, respectively. The RAW data files contained the values of inphase and quadurature voltage signals of a series of frequencies, along with an identifying fastener number. CRK files, on the other hand, are simply RAW data files to which one additional piece of information has been added-- the crack size associated with each particular fastener number.

Program ADDCRK (add crack information) inputs a RAW-data file, lets the operator designate cracked fasteners, and writes this information out in a CRK data file. This operation is performed on a RAW data file, taken on a standard wing panel, prior to subsequent AID, PAID (partial AID) or regression analysis.

The LISTER program is a utility program which will list on the console the contents of a RAW or CRK data file which has been stored on disk. Optionally, an AID prediction can be performed on the data or any transform may be computed and listed out.

The SEND program is used to transfer the contents of a CRK data file via the systems serial I/O connector and a modem to the CDC 6500 computer. The CDC 6500 is Battelle's large mainframe compouter and is used to run regression and AID analysis on MFEC data.

Program PAID (partial AID) provides a means to perform an interactive partial AID analysis on the MFEC system without having to transfer data to another computer. This program was used to make comparative evaluation of potential crack/no crack algorithms and to gain insight into the defect information contained in MFEC data. The PAID program also includes means to compute and evaluate nonlinear regression formulas as decision algorithms.

4. SYSTEM OPERATION

There are basically two different modes under which the MFEC system can be operated -- system calibration and repetitive testing. The following section is devoted to a brief explanation of the steps one would follow for each mode.

A. Calibration. System calibration is concerned mostly with training the system computer to correctly interpret the eddy current response from a standard set of fasteners to identify holes with cracks. Assuming that the proper coil has been selected, that suitable calibration standards are available, and that an appropriate MBL (master balance) file is available, one begins by balancing the test probe.

One essential characteristic of probe balancing, especially when regression analysis is used, is that the probe position used during balancing be highly repeatable. As detailed in the section under Field Evaluation (Section V), we balanced the probe in air well away from any metal. The probe may be balanced anywhere that is repeatable, as long as the same probe location is available during testing. Probe balancing is accomplished by using the program TSTBAL.

Once the probe is balanced, the next step is to gather data from the sample fasteners. This is accomplished using the program ACQUIR. The option code specified in the ACQUIR program depends somewhat upon how the repetitive testing is to be accomplished. If temperature variations are thought to be a problem, the option should include a balance compensation reading. This involves taking two readings for every fastener; one with the probe in position over the fastener, and the second with the probe in the balancing position. The second reading measures the drift of the probe due to temperature and is subtracted from the first to compensate for the drift. If this step is included, it should also be included in the repetitive testing. In any event, the option code specified should also include storing the raw data values on the floppy disk.

Once the data has been collected, crack information must be added to change it into a learning set. This is done with the program ADDCRK by reopening the data file generated in the previous step, and then typing in the fastener number and crack size of each cracked fastener. Any fastener not entered during the program is assumed to be uncracked.

The next step is the actual data analysis, or curve fitting. For this project this involved sending the learning set of data to the mainframe computer, with the program SEND. Since the program used to generate the regression equation will vary from one computer to the next, we will not list the exact steps involved, since they are specific to our computer and no other. If the regression were performed on the LSI II computer, this step would be unnecessary.

After the regression equation has been generated, it is tried on the original learning data using the program PAID. PAID (partial AID) performs many of the functions of AID, and also computes linear and nonlinear regressions. If the new regression is successful in splitting the learning data, the new transform is added to the transform library, which is essentially the regression equation, and a new decision tree file (AID file) is set up using the program EDTAID (edit AID tree file). The AID structure is still used for data analysis itself, though the only split made is on the regression equation just generated.

More likely than not, the first regression equation will not work very well with the data set, and a new regression must be generated. The coefficients generated by the regression depend very specifically on the crack size input to the learning set and it is not clear exactly how the eddy current response varies with crack size. That is to say, the eddy current response varies in a nonlinear fashion with crack size, and it is this nonlinear behavior we are trying to model, not the actual crack size. Several trial and error attempts are usually necessary to generate a usable regression equation.

After an equation is generated which is successful on the learning data, it should be evaluated on new data. Assuming that it works well with the new data. The MFEC system is then ready to do the repetitive testing.

B. Repetitive Testing. The repetitive testing mode of the MFEC system is just a shortened version of the system calibration. The only two programs necessary are TSTBAL and ACQUIR. The probe is first balanced in exactly the same position as when calibrating. Once balanced, the program ACQUIR is used to acquire data. The option code used, however, is different and should include the following:

(a) List crack prediction on the console -- lists either 0 for "no crack" or 100 for "crack" for every fastener tested.

(b) Store raw data values on the disk -- used to obtain permanent record of signal voltage readings for later review.

(c) Use a balance compensation reading (if it was used during calibration)

(d) Display the crack prediction on the operators remote panel -- illuminate yes/no light.

SECTION IV

LABORATORY EVALUATION

After completing construction of the digital system it was first checked out operationally in a qualifying run and then used to refine the procedures.

1.QUALIFYING RUN

The digital MFEC system was initially evaluated by repeating the same tests used to evaluate the side-coil in the one-month study conducted between Phase I and Phase II. The final report of that side coil evaluation program is included as Appendix A.

Table I is a summary of the results obtained in the side coil development study and the "qualifying" runs made using the new system and the same side coil. The side coil with its balance coil was packaged into a probe for the Phase II run. Different operators conducted these tests due to changes in project personnel. The total number of fasteners differs because panel I-7 which was used to provide a fastener for balancing in the side-coil evaluation and had no "cracked" holes, was not tested in the Phase II run.

The results of the qualifying test run were not quite as good as those obtained in the run made during the side-coil study, however, they are close enough to indicate the system was operating satisfactorily.

2. COIL DESIGN

The most critical parameters which govern the efficiency of an eddy current coil in a given application are the type of coil used, its physical dimensions, and its electrical characteristics. There are various types of coils; among them are probe, cup-core, U-core (or side-core), reflection, and pancake coils. Each type of coil is best suited for certain applications, though there is some overlap between them. The physical dimensions determine the "field of view" of the coils, as well -

TABLE I

COMPARISON OF RESULTS OF QUALIFYING RUN MADE WITH PHASE II DIGITAL MFEC SYSTEM AND RUN MADE WITH SAME COIL AND TEST PROCEDURE WITH BREADBOARD SYSTEM

	Side Coil Development Study			Phase II Study New System		
		Correct Calls			Correct Calls	
Condition	Possible	No.	%	Possible	No.	%
No Crack	72	67	93.1	65	56	86.2
0.1" Crack	35	32	91.4	30	27	90.0
0.2" Crack	60	58	96.7	55	50	90.9
0.3" Crack	20	20	100.0	20	20	100.0

as some of its electromagnetic parameters, and are important for that reason. The electrical characteristics refer mainly to the reactance and resistance of the coil, and determine how well a coil will match the circuitry of the eddy current system. The last may also refer to any impedance matching made between the coil and the system.

The selection of these parameters is not, as yet, a well established procedure, but is guided mainly by rules of thumb and the experience (and, at times, the intuition) of the designer. Some progress has been made at systematizing the design of eddy current coils, but only for applications far simpler than those involved in this program. The accurate detection of small (< 0.1") fatigue cracks through 0.2"-0.4" of aluminum is, in itself, a difficult problem; the complex geometrical shape of the splice joint greatly increases not only the difficulty of the coil design, but also the analysis of the data.

The design specifications for the coil were as follows:

(a) Good sensitivity to small (0.1") saw cuts through at least 0.25" of aluminum

(b) Relative insensitivity to extraneous variables such as lift-off, conductivity, temperature variations, and centering over the fastener.

(c) In case of geometrical conflicts, the coil was to be optimized for the row nearest the edge of the double-row fastener wing splice, which is the most probable location of crack initiation.

A. REVIEW OF PAST WORK: The type of coil used at the inception of this program was a cup-core coil, and was shown to have good sensitivity to saw cuts around steel fasteners, but to have insufficient sensitivity to saw cuts around titanium fasteners. This resulted in a short study (described in Appendix A) that was to compare the defect sensitivity of the cup-core coil which tested the full fastener circumference with another type coil, then called a side-core coil which tested only a quadrant of the fastener circumference. Though the sensitivity seemed to be improved, the decision tree was complicated and not suitable for the final system. For this reason, it was decided that some effort should be spent on improving the coil in the Phase II. But before discussing the improvements that were eventually made in the type of coil used, it would be appropriate to

reexamine the cup-core coil and the side-core coil to determine how they work, and what their deficiencies were.

B. Cup-Core Coils. A rule of thumb guide to the maximum depth of penetration that can be achieved with a circular coil, operating at a given frequency is

$$d = \mathrm{Min}\ (D, \delta) \tag{2}$$

where d is the depth of penetration, D is the diameter of the coil, and δ is the skin depth at the operating frequency. However, coils of this type are extremely sensitive to edge effects, and, in general, should not be used any closer than two to three diameters to an edge, if at all possible.

Because of this, the Phase I investigators decided to use a cup-core coil, which is essentially a ferrite channel wrapped around the coil. The consequences of this are threefold. First, the edge effects are greatly reduced, allowing one to center the coil over the fastener with essentially no coil output due to the splice joint. Secondly, the depth of penetration is reduced. The exact amount of reduction depends somewhat on the dimensions of the core, but is estimated by

$$d_{cc} = \mathrm{Min}\ (D/3, \delta) \tag{3}$$

Thirdly, the region of maximum sensitivity is confined essentially to the cylindrical volume defined by the edges of the ferrite channel, and decreases rapidly to either side.

An approximate relation which describes the minimum detectable crack size as a function of depth can be derived if it is assumed that the cup-core is centered over the fastener. In order to obtain reliable indications, it is assumed that the crack must extend through the region of maximum sensitivity. For 1/4" titanium fasteners, this can be expressed by

$$C_L = D/2 - .125 \tag{4}$$

where C_L is the length of the smallest crack that can be detected with good reliability. From Equation (3), the maximum depth of penetration, if the test frequency is properly chosen, is

$$d = D/3 \tag{5}$$

where d is the depth. Thus, Equation (4) is rewritten as

$$C_L = (\frac{3}{2}d - .125) \tag{6}$$

But, since Equation (6) represents only the limiting case, and a negative value of C_L makes no sense, the above is rewritten as

$$C_L = \text{Max } (\frac{3}{2}d - .125,\ 0.05) \tag{7}$$

It should be noted that this equation represents a conservative estimate of the length of the smallest detectable crack as a function of depth, and applies only to non-ferromagnetic fasteners.

From Equation 7, the estimate of C_L at a depth equal to 0.25" is

$$C_L = 0.25'' \tag{8}$$

which is well above the Air Force requirement of 0.1" or less. Thus, as long as the cup-core is centered above the fastener, the size of defect it can detect is limited, and this limit is above what the Air Force can accept.

C. Side-Core Coil. The capabilities and limitations of the side-core coil are not as easy to comprehend as those of the cup-core, because of its complicated geometry. However, some insight can be gained if it is recognized that the side-core coil is nothing more than a misshaped version of a coil with a U-shaped core, and that some of the generalities which apply to the U-core will also apply to the side-core.

As an electrical analog of St. Venant's principle in elasticity, it is assumed that two coils which induce the same electromagnetic boundary conditions on a metal sample will generate essentially equal eddy currents. This assumption allows the decomposition of the U-core coil into two series-aiding probe coils with ferrite centers identical to the legs of the U-core, as illustrated in Figure 5. These probes, being much smaller than a cup-core coil, inspect a smaller volume of the wing splice; thus, the sensitivity to smaller defects is increased. In addition, the location of the probes is variable, allowing one to place the region of maximum probe sensitivity in line with the expected location of any defects, again increasing the sensitivity to small defects. It was the combination of these two effects which resulted in the enhanced sensitivity to the 0.2" and smaller sawcuts. Note, however, that only one leg of the U-core coil can detect any defects, since the other leg is too far away.

The most serious objection to the U-core coil is in its sensitivity to liftoff. Since it acts as essentially two probe coils in series-addition, the voltage change across one coil is added to the voltage change across the other, thereby doubling the total output and undoubtedly overwhelming any defect indications. This could result in problems when attempting to inspect painted surfaces, because paint thicknesses, in general, are not well controlled. A cursory examination of Figure 5, though, reveals the somewhat obvious solution; i.e., liftoff outputs can be reduced or eliminated by wiring the coils in series-opposition. Since the series-aiding effect comes about from the ferrite bridge between the two legs, a series-opposition coil can only be made by eliminating the U-core and winding two separate coils. The result will be a coil with the same defect sensitivity as a similar U-core coil, but without its liftoff effect, and was the type finally chosen in this program.

D. Differential Probe Coil. The type of coil described above is called a differential probe, because it consists of two probe coils connected in a differential mode. Four such coils were constructed in the course of the program, but the first two are the most important, and are discussed in detail.

The first coil, DPI, was wound on two ferrite rods with a diameter of 0.205. The mean diameter of the coil windings was 0.24" which meets the criteria of Eq. (2), and the coils were positioned so that the edge of the coil (i.e., the region of maximum sensitivity) was at the location where cracks were expected to form. The probe is shown in Figure 6.

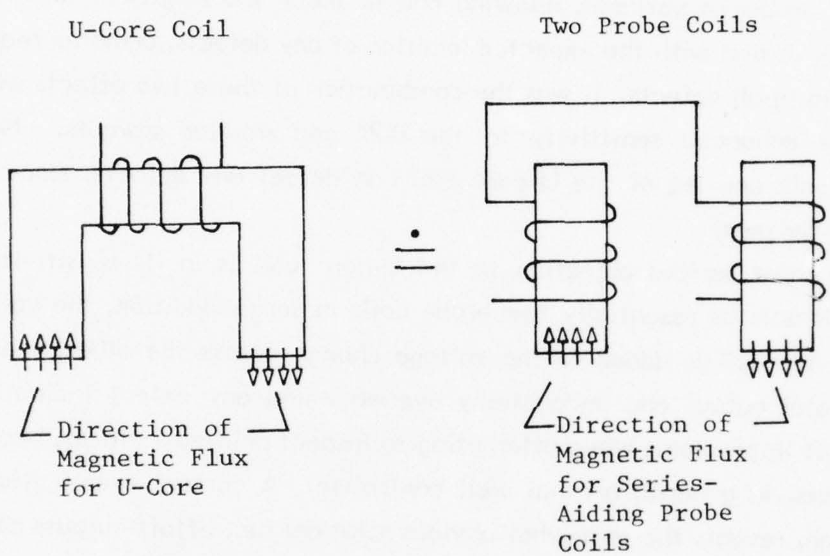
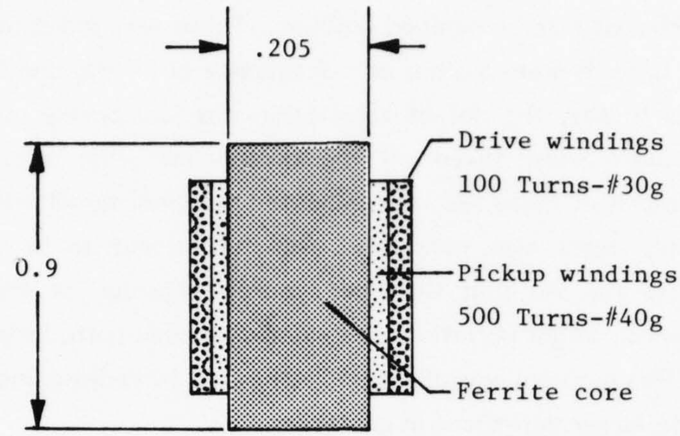
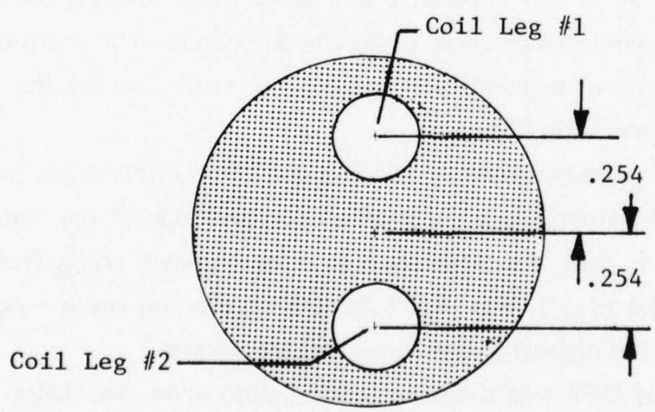


FIGURE 5. DECOMPOSITION OF A U-CORE COIL INTO TWO EQUIVALENT PROBE COILS



Leg #1 of Differential Probe
(Second leg identical)



Lucite Coil Holder Showing
Position of Two Coils

FIGURE 6. SKETCH OF DIFFERENTIAL PROBE 1
(DP1)

The defect sensitivity of DP1 was evaluated on test plates of various thicknesses with different sized machined notches. These test indicated that at a 1/4"inch depth, 0.1" defects were visible at a frequency of 94 Hz, and 0.2" defects at 335 Hz. That is to say, the defect sensitivity was just barely marginal. In addition, measurements were taken on the double-row wing samples in our laboratories. The results of these test also indicated marginal sensitivity.

The latter tests also indicated what turned out to be the biggest obstacle of the program, and that was the accurate location of the coil with respect to the fastener. Slight variations in centering caused quite large variations in the coil output. This problem was alleviated somewhat by redesigning the coil so that it could tolerate larger variations in centering.

At this point, DP2 (Figure 7) was designed to alleviate the above mentioned problems. To increase the defect sensitivity, the depth of penetration was increased by increasing the size of the coil. At the same time, the coils were positioned further from the center of the fastener, to reduce the effects of centering.

Rectangular ferrite rods (1/4" x 1/2" x 1") were used for the coil poles so that the effective diameter of the coil could be increased while keeping the edge of the coil as far away as possible from other fasteners and edges. The sharp edges of the ferrite were ground down to prevent damaging the wires, giving the coils the roughly ellipitical shape shown in Figure 8.

Since one of the main purposes in building and using differential probes was to reduce the effect of liftoff, some mention should be made of our success. The most striking example is that the difference in outputs, when going from no liftoff to infinite (very large) liftoff, was less than 10% of the full scale range of the eddy current system, at the highest (most sensitive) frequency.

The evaluation of DP2 was made by taking data from the laboratory wing panel samples on one group of eight fasteners. Among these fasteners was one with a 0.3" sawcut, two with 0.2", and one with 0.1". The remaining four were supposedly defect free.The resulting data, shown in Figure 9, clearly grouped fastener 438, with no sawcut, among the fasteners with sawcuts. A later penetrant examination of the fastener indicated a crack in the lower wing panel, giving good evidence of the defect sensitivity of DP2.

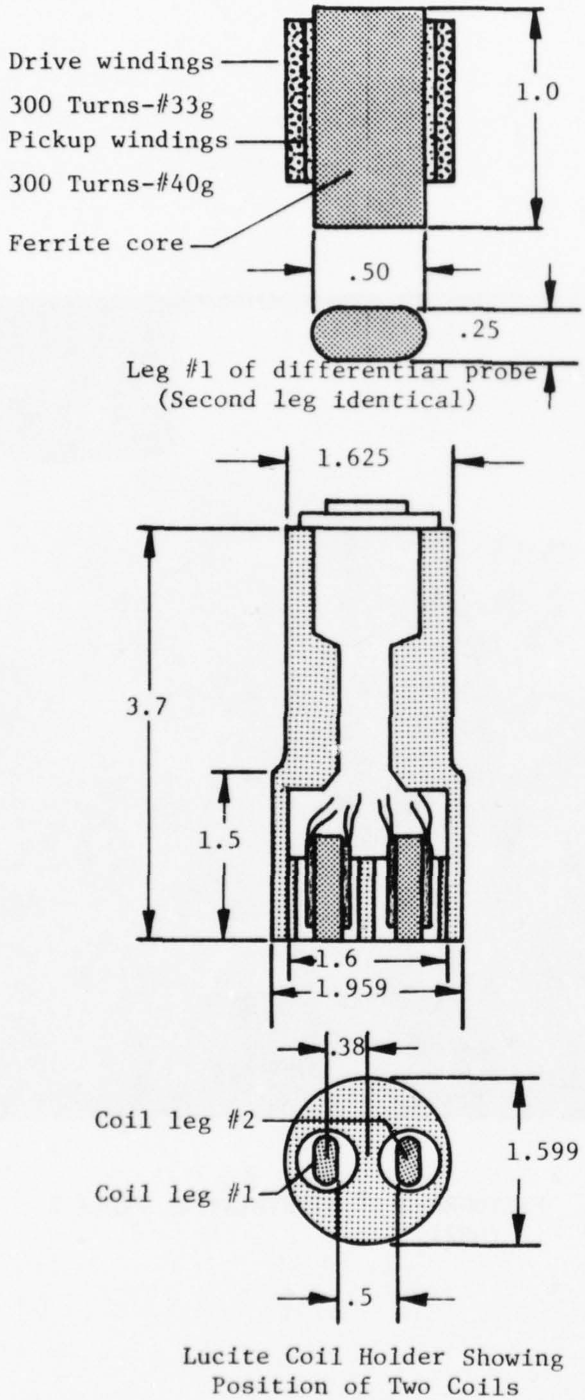
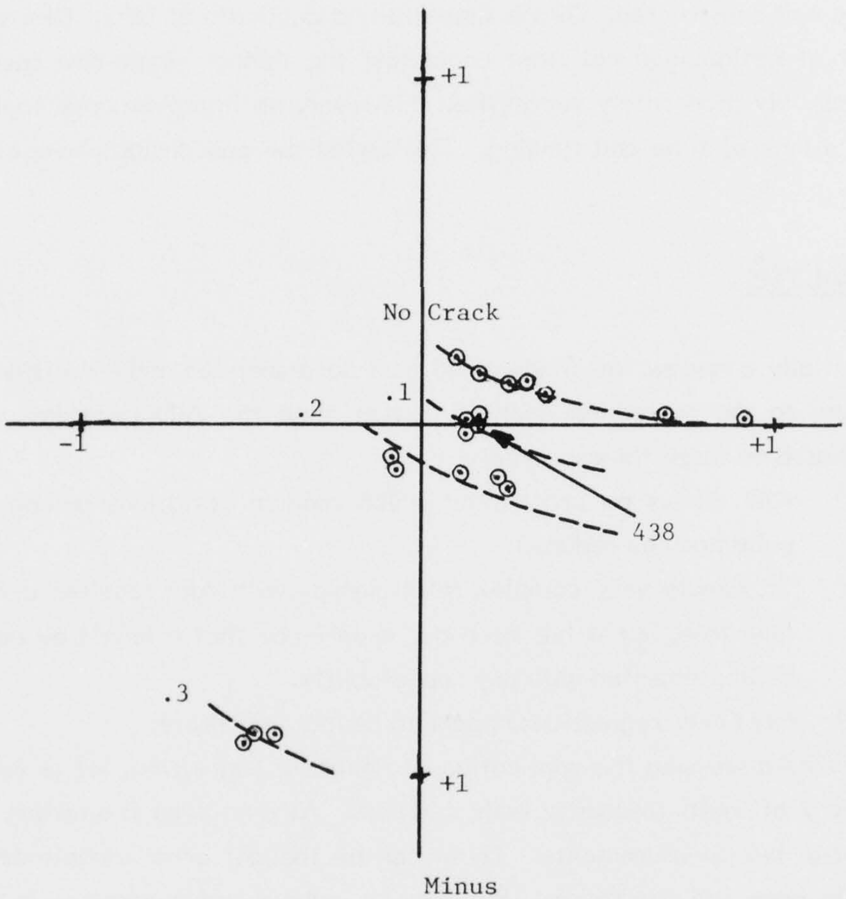


FIGURE 7. SKETCH OF DIFFERENTIAL PROBE 2 (DP2)

FIGURE 8. PHOTOGRAPH OF DIFFERENTIAL PROBE 2
(DP2)



Note that the response of fastener 438 is grouped with the defective fasteners. The presence of a real crack was later confirmed by a penetrant examination.

FIGURE 9. IMPEDANCE PLANE PLOT SHOWING THE OUTPUT OF COIL DP2 (95 HZ) AS A FUNCTION OF CRACK SIZE (NO CRACK; 0.1", 0.2" and 0.3" SAWCUTS)

In addition to DP1 and DP2, two other differential probes, DP3 and DP4, were designed and constructed. DP3 is essentially a duplicate of DP2. DP4 was a first attempt at designing a coil that could test the thinner single-row fastener joints, but was only moderately successful. However, no improvements could be made due to a lack of time and funding. This ended the coil design phase of this program.

3. DATA ANALYSIS

Initially a review was made of all past data analyses and a decision was made to return to the regression analysis, rather than the AID program. This decision was based on three things, namely:

(a) AID allows no process by which random variations among data points can be reduced.

(b) To handle very complex relationships with AID requires a fairly long tree, but it has been our experience that a long tree cannot be implemented with any repeatability.

(c) Nonlinear regressions appear to be more accurate.

Before discussing the application of nonlinear regression, let us review the basic theory of multi-frequency eddy currents. At any given frequency, it is possible to make two measurements. These can be thought of as magnitude and phase, or as inphase and quadrature. We can use inphase and quadrature in what follows without any loss of generality. In the sample we are testing, there are several variables which can mask or distort the item we are most intersted in measuring. Suppose there are n such variables, Z_1 through Z_n, and that we are interested in determining one or more. In general, we may write

$$IP_i = x_i = f_i\ (Z_1, Z_2, \cdot \cdot \cdot, Z_n) \qquad (9)$$
$$Q_i = y_i = g_i\ (Z_1, Z_2, \cdot \cdot \cdot, Z_n)$$

where IP_i and X_i are the inphase voltage at frequency i, Qi and Yi are the quadrature, and f_i and g_i describe their respective relationships to the Z_n's. The principal assumption of linear multifrequency theory is that changes in the X_i and Y_i can be related to changes in the Z_i through a linear Taylor's series expansion, or (Einstein's summation convention)

$$\Delta X_i = \frac{\partial f_i}{\partial Z_j} \Delta Z_j$$

$$\Delta y_i = \frac{\partial g_i}{\partial Z_j} \Delta Z_j \tag{10}$$

The nonmenclature in Eq. (10) can be cleaned up by ignoring the differences between the X's and Y's, and writing

$$\Delta X_i = \frac{\partial F_i}{\partial Z_j} \Delta Z_j \tag{11}$$

where F_i represents the functional relationship between the X's and Z's. Now, if there are n different Z's, n different X's are required. But since there are two X's per frequency, n/2 frequencies are required. We may rewrite Eq. (11) in matrix form as

$$\begin{Bmatrix} \Delta X_1 \\ \cdot \\ \cdot \\ \cdot \\ \Delta X_n \end{Bmatrix} = \begin{bmatrix} \frac{\partial F_1}{\partial Z_1} & \cdots & \frac{\partial F_1}{\partial Z_n} \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \frac{\partial F_n}{\partial Z_1} & \cdots & \frac{\partial F_n}{\partial Z_n} \end{bmatrix} \begin{Bmatrix} \Delta Z_1 \\ \cdot \\ \cdot \\ \cdot \\ \Delta Z_n \end{Bmatrix} \tag{12}$$

If the forms of the F's are known, the matrix can be inverted. Otherwise, any single row of the inverse can be found by measuring various X's and using linear regression to find the equation which describes the change in some variable Z with the changes in the X's.

The critical assumption of the linear theory, first described by Libby, is contained in Eq. (10); that is the fact that the relationshhip is assumed to be linear. The question, then, is what if it isn't? A simple example, involving only one frequency and two variables is given. Instead of a linear Taylor's series expansion, we expand to the second degree. Thus,

$$\Delta X = \frac{\partial f}{\partial Z_1} \Delta Z_1 + \frac{\partial f}{\partial Z_2} \Delta Z_2 + \frac{1}{2} \frac{\partial^2 f}{\partial {Z_1}^2} \Delta Z_1^2 + \frac{1}{2} \frac{\partial^2 f}{\partial Z_2^2} \Delta Z_2^2 + \frac{\partial^2 f}{\partial Z_1 \partial Z_2} \Delta Z_1 \Delta Z_2 \tag{13}$$

$$\Delta Y = \frac{\partial g}{\partial Z_1} \Delta Z_1 + \frac{\partial g}{\partial Z_2} \Delta Z_2 + \frac{1}{2} \frac{\partial^2 g}{\partial Z_1^2} \Delta {Z_1}^2 + \frac{1}{2} \frac{\partial^2 g}{\partial Z_2^2} \Delta Z_2^2 + \frac{\partial^2 g}{\partial Z_1 \partial Z_2} \Delta Z_1 \Delta Z_2$$

We immediately see that the inversion of Eq. (13) is difficult, especially if we are required to know the forms of both first and second derivatives of f_i and g_i. But it is fairly obvious that it will involve fractional powers of X_i and Y_i.

Another way to solve Eq. (13) is to assume that the Z's can be written as a polynominal expansion in the X's. Thus

$$\Delta Z_1 = \sum_{i=1}^{n} \sum_{j=0}^{i} A_{ij} X^{i-j} Y^j + K$$

$$\Delta Z_2 = \sum_{i=1}^{n} \sum_{j=0}^{i} B_{ij} X^{i-j} Y^j + K \qquad (14)$$

which can be solved by the process of nonlinear regression to any order n desired. The same is true for more complex situations involving more Z's and more frequencies. The regression technique which solves Eq. (14) is no different than the one which solves Eq. (12). The fundamental difference is in allowing the terms on the right hand side of Eq. (14) to become nonlinear. The general form of Eq. (14) which was used to model crack length is demonstrated in Eq. (15), where we have reverted back to the X-Y notation for inphase and quadrature.

$$C_L = \sum_{i=1}^{4} [A_i X_i + B_i Y_i + C_i X_i^2 + D_i Y_i^2 + E_i X_i Y_i] + K \qquad (1)$$

Notice that the only nonlinear terms allowed were within a given frequency (i.e., involving the inphase and quadrature of only one frequency at a time), whereas a complete nonlinear solution would have mixed all components of all frequencies. Note also that the highest power in Eq. (15) is the second. These last two items were both done to reduce the complexity of the equation, and the computer time required to solve it.

A. Regression Equations. As was mentioned in the section on coil design, an examination of some preliminary raw data indicated that one fastener, which was thought to be in a noncracked hole, gave eddy current indications which were similar to the fastener holes with sawcuts. A subsequent PT examination confirmed the existence of a natural crack. The culmination of this chain of

events was that we could no longer be certain of exactly what our test samples contained. Several other supposed non-cracked fasteners also gave suspicious readings, but the inside surfaces were so badly scored from removing and replacing the fasteners that no definite PT indications were obtained.

The basic theory of regression and computer training absolutely requires what is known as uncontaminated data sets. The slightest bit of contamination (i.e., imprecise knowledge) in the data set reduces considerably the accuracy of the regression and the ability of the computer to train itself. The import of this is that the regressions made for the system before it was taken to Lockheed-GA. were contaminated. Once the system was in Georgia, it was necessary to recalibrate the system, but no computer was available to repeat the regression solution. At this time, a decision was made to eliminate all suspicious fasteners from the data sets, but without redoing the regression. The remaining fasteners, twenty-two in number, were then used to recalibrate the system and perform the SIEP inspection.

Once the inspection was completed and the system returned to Battelle Columbus, the regression was recomputed using the new set of twenty-two fasteners. At this time, it would be advantageous to examine the regression used in Georgia along with the new one, and to try to answer the question of whether multifrequency is better than single frequency.

Results of the regression used as the decision algorithm for the SIEP inspection is shown in Figure 10. The abscissa is fastener hole number, and is grouped according to crack size. The ordinate is the value of the regression equation obtained by substituting into the following equation the values obtained for the inphase and quadrature at the low frequencies. Each measurement was repeated five times to gain an appreciation of the variation obtained. The regression equation used was

$$\begin{aligned} C_E = {} & 4.64\ X_1 + 5.71\ Y_1 + 10.62\ X_2 - 4.83\ Y_2 \\ & + 6.24\ X_3 - 6.24\ Y_3 - 1.57\ X_4 + 1.22\ Y_4 \\ & - 3.53\ X_1^2 - 4.86\ Y_1^2 - 2.18\ X_2^2 - 0.201\ Y_2^2 \\ & - 0.092\ X_3^2 + 0.629\ Y_3^2 + 0.270\ X_4^2 + 0.371\ Y_4^2 \\ & + 1.20\ X_1Y_1 + 2.84\ X_2Y_2 - 0.656\ X_3Y_3 - 0.135\ X_4Y_4 + 1.17 \end{aligned} \qquad (15)$$

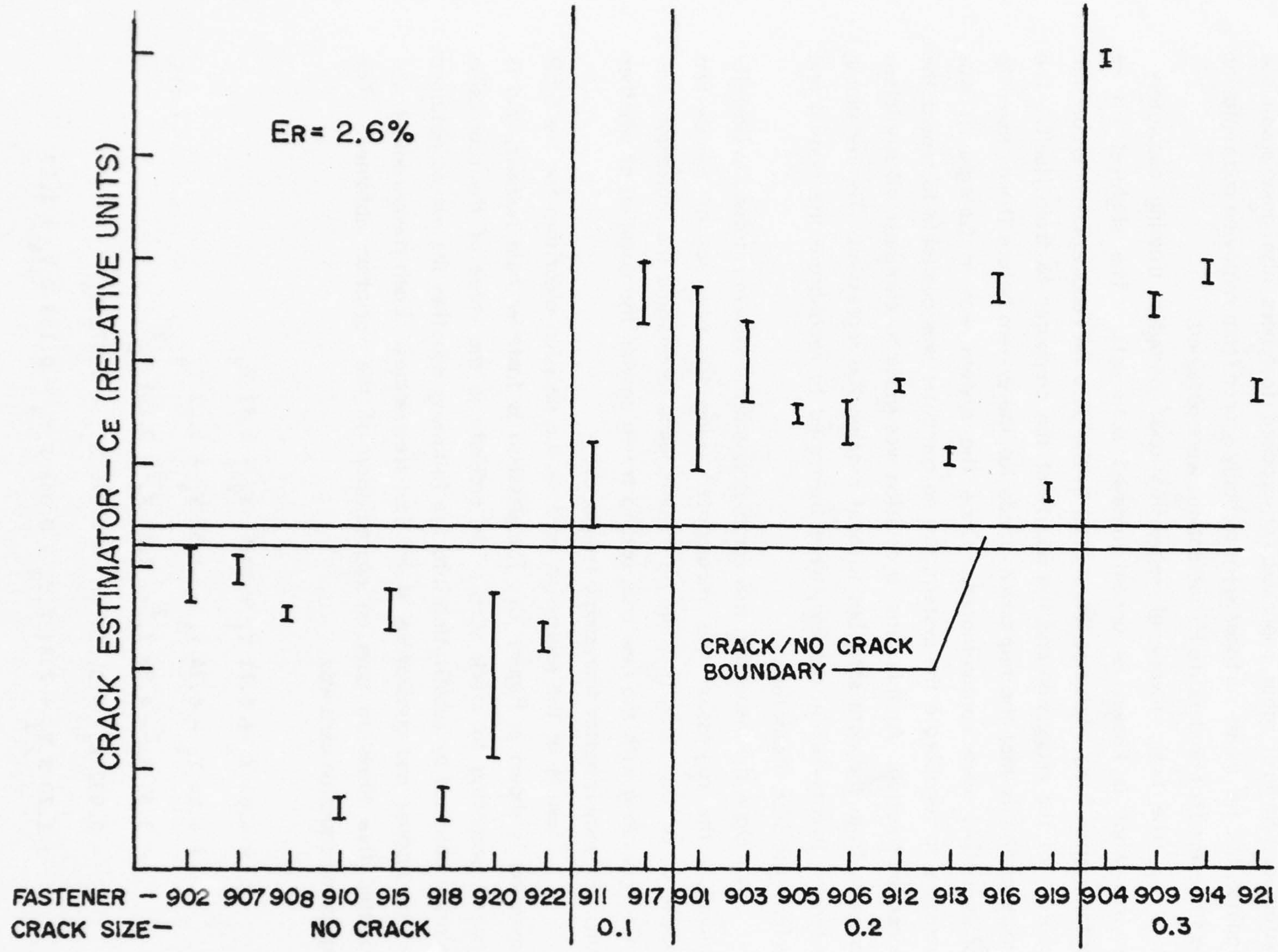


FIGURE 10. CRACK ESTIMATOR VS CRACK SIZE - MULTIFREQUENCY ANALYSIS (THE RANGE OF VALUES INDICATES THE SPREAD FROM FIVE INDEPENDENT SAMPLES)

where C_E stands for crack estimator, the X_1 through X_4 are the inphase measurements at the four frequencies, and the Y_1 through Y_4 are the quadrature measurements. Note that there is a definite separation of the cracks from the noncracks in Figure 10.

Normally, the ability to separate a series of measurements into two groups would be measured by the difference of the ratios of standard deviation to mean of each group. However, since each group is rather small, we will define a different variable, denoted as the efficiency ratio, E_R, to measure the efficiency of separation. This quantity is given by

$$E_R = \frac{\mathrm{Min}(C_E^{\mathrm{crack}}) - \mathrm{Max}\ (C_E^{\mathrm{noncrack}})}{\mathrm{Max}(C_E^{\mathrm{crack}}) - \mathrm{Min}\ (C_E^{\mathrm{noncrack}})} \qquad (16)$$

The efficiency ratio for Eq. 15 is 2.6 percent, that is, the width of the separation between cracks and noncracks is only 2.6 percent of the total range of crack estimators obtained with the sample fasteners.

The main emphasis of this program was to separate cracks from noncracks, which is accomplished by Eq. (15). However, it must be noted that small variations in readings on fasteners in the wing could easily cause noncracks to read slightly higher and cracks slightly lower, resulting in miscalls.

Once the system was returned from Georgia, the regression was repeated with our uncontamniated set of fasteners, as shown in Figure 11. The equation for this crack estimator is

$$\begin{aligned} C_E = {} & 6.42\ X_1 + 2.64\ Y_1 + 2.19\ X_2 - 0.097\ Y_2 - 7.12\ X_3 \\ & - 1.43\ Y_3 + 74.1\ X_4 - 10.34\ Y_4 - 7.15\ X_1^2 - .906\ Y_1^2 \qquad (17) \\ & + .193\ X_2^2 + 2.92\ Y_2^2 + 2.00\ X_3^2 + .702\ Y_3^2 - 12.14\ X_4^2 \\ & - 1.26\ Y_4 + 2.26\ X_1Y_1 + 3.41\ X_2Y_2 - .336\ X_3Y_3 + .379\ X_4Y_4 \\ & - 106 \end{aligned}$$

As can be seen in Figure 11, this estimator is much improved over the one used in Georgia, with an efficiency ratio equal to 15.1 percent.

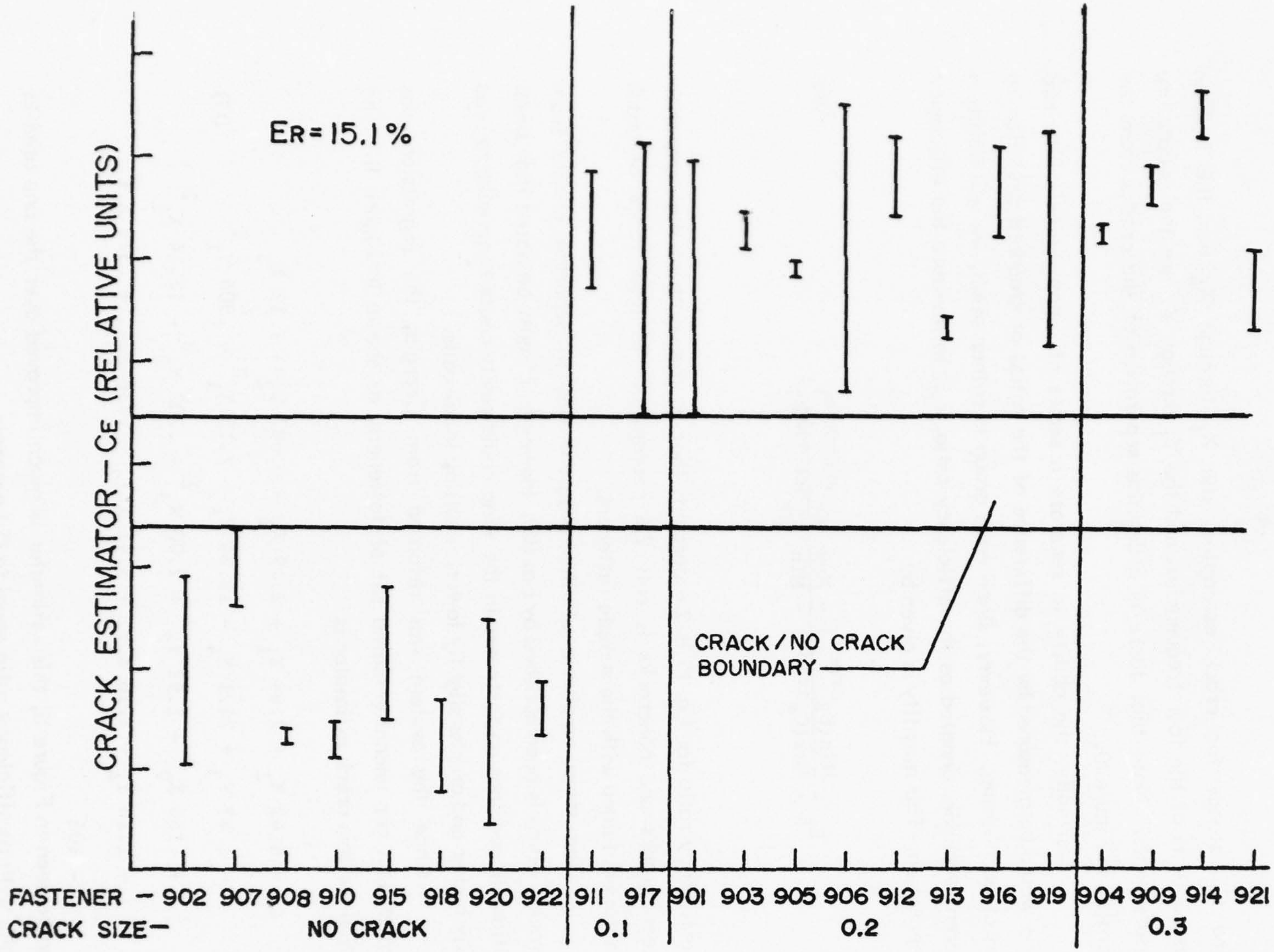


FIGURE 11. CRACK ESTIMATOR VS CRACK SIZE - MULTIFREQUENCY ANALYSIS (THE RANGE OF VALUES INDICATES THE SPREAD FROM FIVE INDEPENDENT SAMPLES)

B. Single Frequency Versus Multiple Frequency. To examine the difference between single frequency and multifrequency, we examine the best crack estimators obtained with the 95 and 335 Hz frequencies alone. The equations used were

$$C_E^{95} = -.566\ X_1 - 1.38\ SY_1 + 2.013 \tag{18}$$

and

$$C_E^{335} = .742\ X_2 - 1.183\ Y_2 + 1.77 \tag{19}$$

As can be seen, the 95 Hz data (Figure 12) does not successfully resolve all cracks, with an efficiency ratio of -7.9 percent (the minus sign occurs because of the numerator of Eq. 16). The 335 Hz data (Figure 13) did successfully resolve all cracks, but had an efficiency ratio of 4.4 percent, between a third and a fourth of that of Eq. (17).

Because of this lower ratio, the crack estimator detailed in Eq. 17 would be less sensitive to unexplained variations in different fasteners, resulting in fewer miscalls. For this reason, we would still recommend the use of multifrequency over single frequency eddy current testing.

C. Frequency Selection. One other aspect of doing data analysis with multifrequency eddy currents is the proper selection of the frequencies used. The criteria to be used is as follows:

(a) At least one frequency should be very sensitive to the variable of interest, in this case, the presence or absence of cracks around fastener holes.

(b) One or more frequencies should be lower than that of (a) in order to contain more information about far-side extraneous variables.

(c) One or more frequencies should be higher than that of (a) to contain more information about near-surface extraneous variables.

As can be seen from Figures 12 and 13, the 335 HZ (13) contains most of the crack information, meeting criteria (a). the 95 Hz (12) is used to meet criteria (b). Note that it also contains crack information, but that it is somewhat distorted.

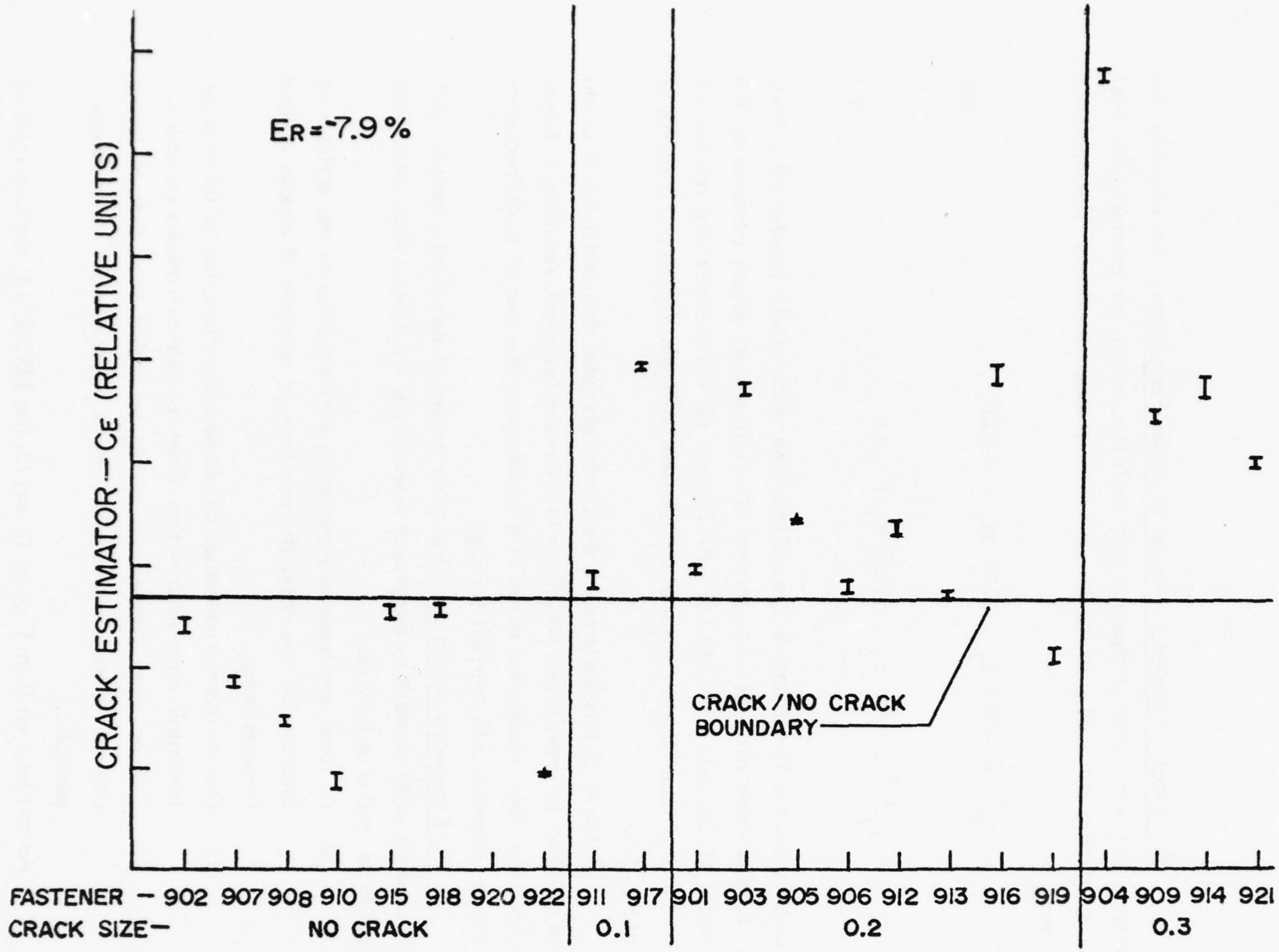


FIGURE 12. CRACK ESTIMATOR VS CRACK SIZE - SINGLE FREQUENCY (95 HZ) (THE RANGE OF VALUES INDICATES THE SPREAD FROM FIVE INDEPENDENT SAMPLES)

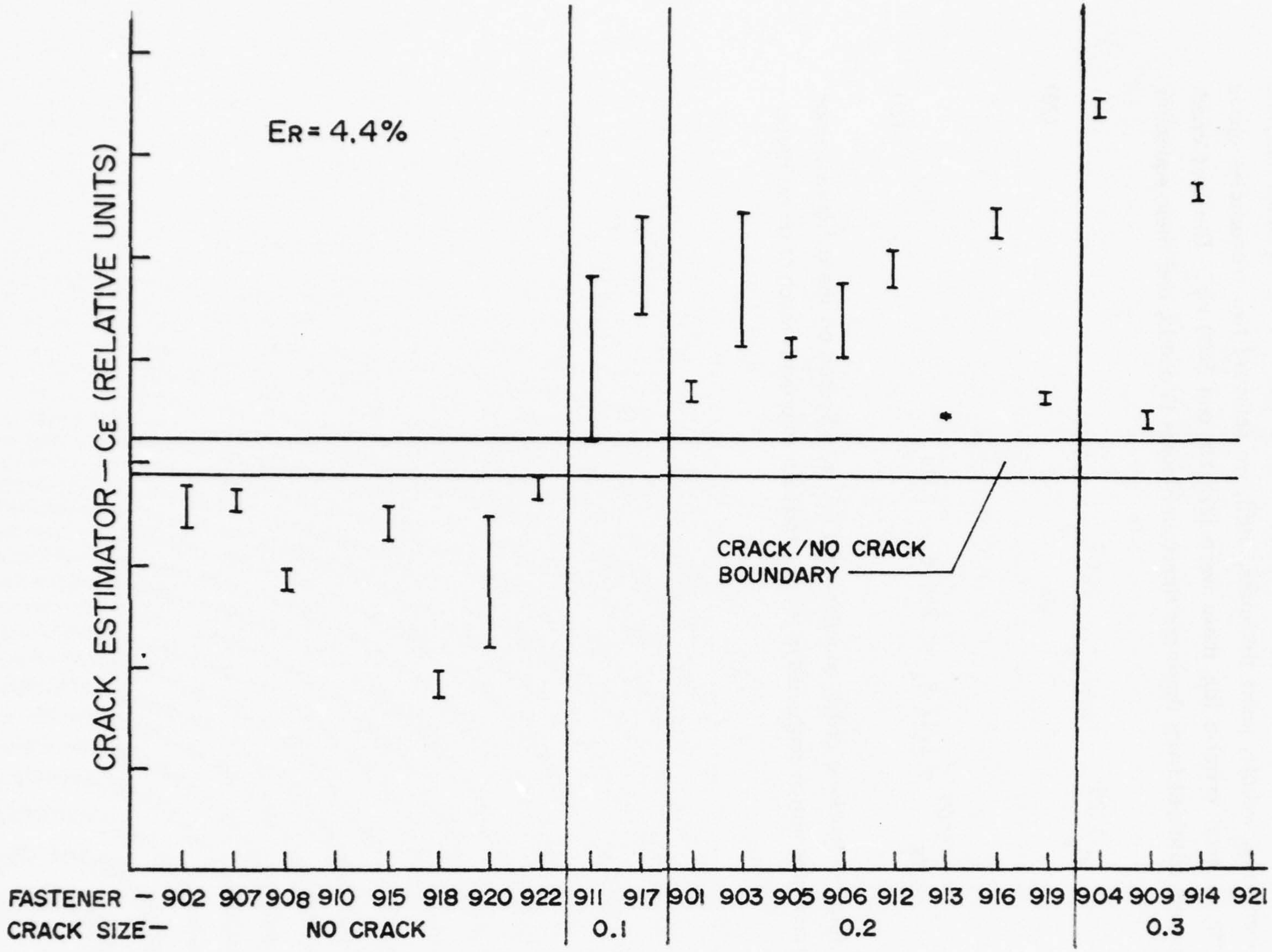


FIGURE 13. CRACK ESTIMATOR VS CRACK SIZE - SINGLE FREQUENCY (335 HZ) (THE RANGE OF VALUES INDICATES THE SPREAD OBTAINED FROM FIVE INDEPENDENT SAMPLES)

Because we were more concerned about near-surface variables (i.e., the fastener head, wobble, paint thickness, etc.), we selected two frequencies above 335 Hz to meet criteria (c); these were 1225 Hz and 5000 Hz. The best crack estimators obtained from these are shown in Figures 14 and 15, and their equations are

$$C_E^{1225} = -.507\ X_3 + .237\ Y_3 + 1.36 \tag{20}$$

and

$$C_E^{5000} = 1.47\ X_4 - .269\ Y_4 - 3.79 \tag{21}$$

Note that no crack-no crack boundary and E_R is indicated on these figures, since the crack information contained in them is too poor to provide much of an estimate.

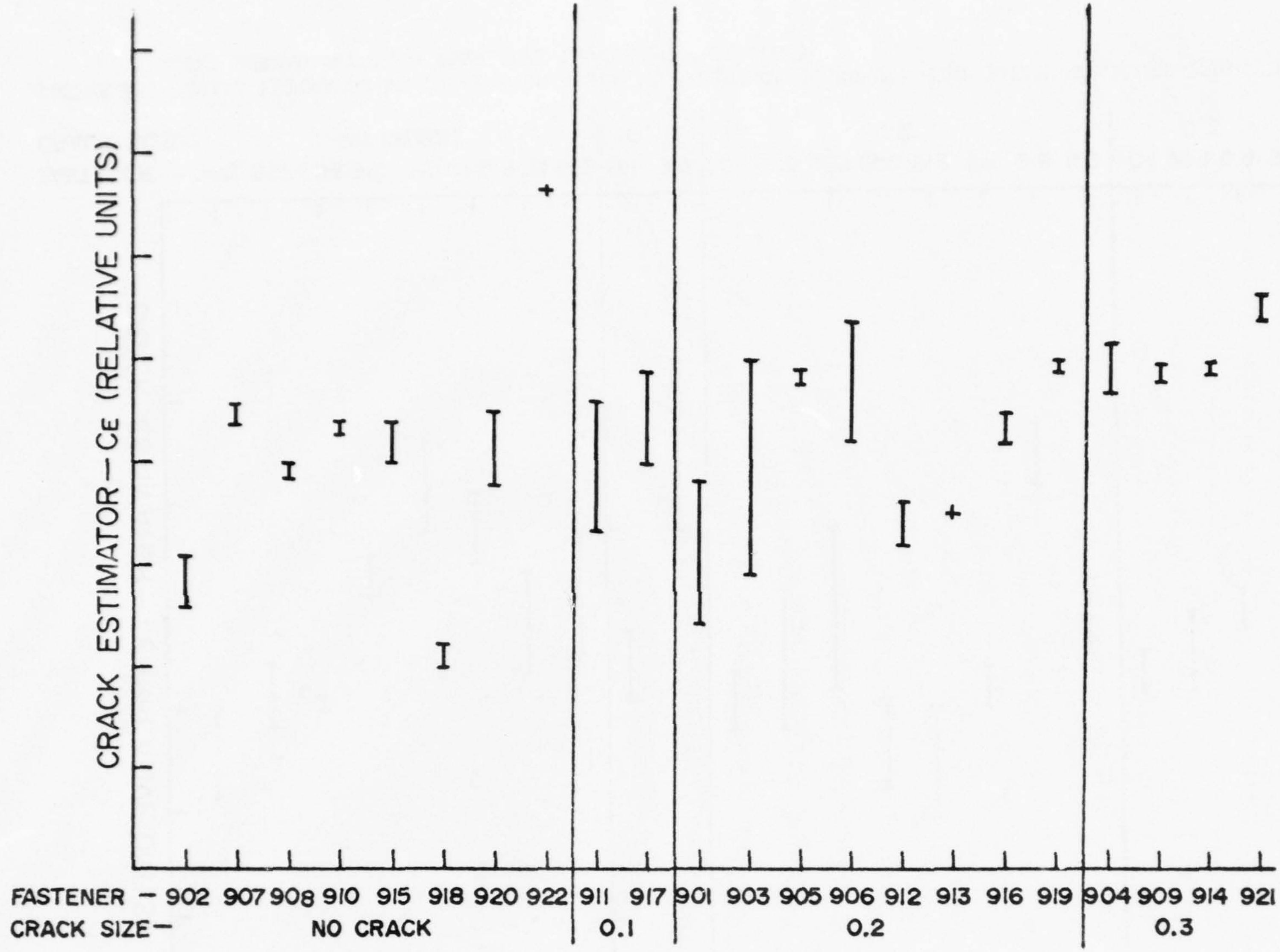


FIGURE 14. CRACK ESTIMATOR VS CRACK SIZE - SINGLE FREQUENCY (1225 HZ) (THE RANGE OF VALUES INDICATES THE SPREAD OBTAINED FROM FIVE INDEPENDENT SAMPLES

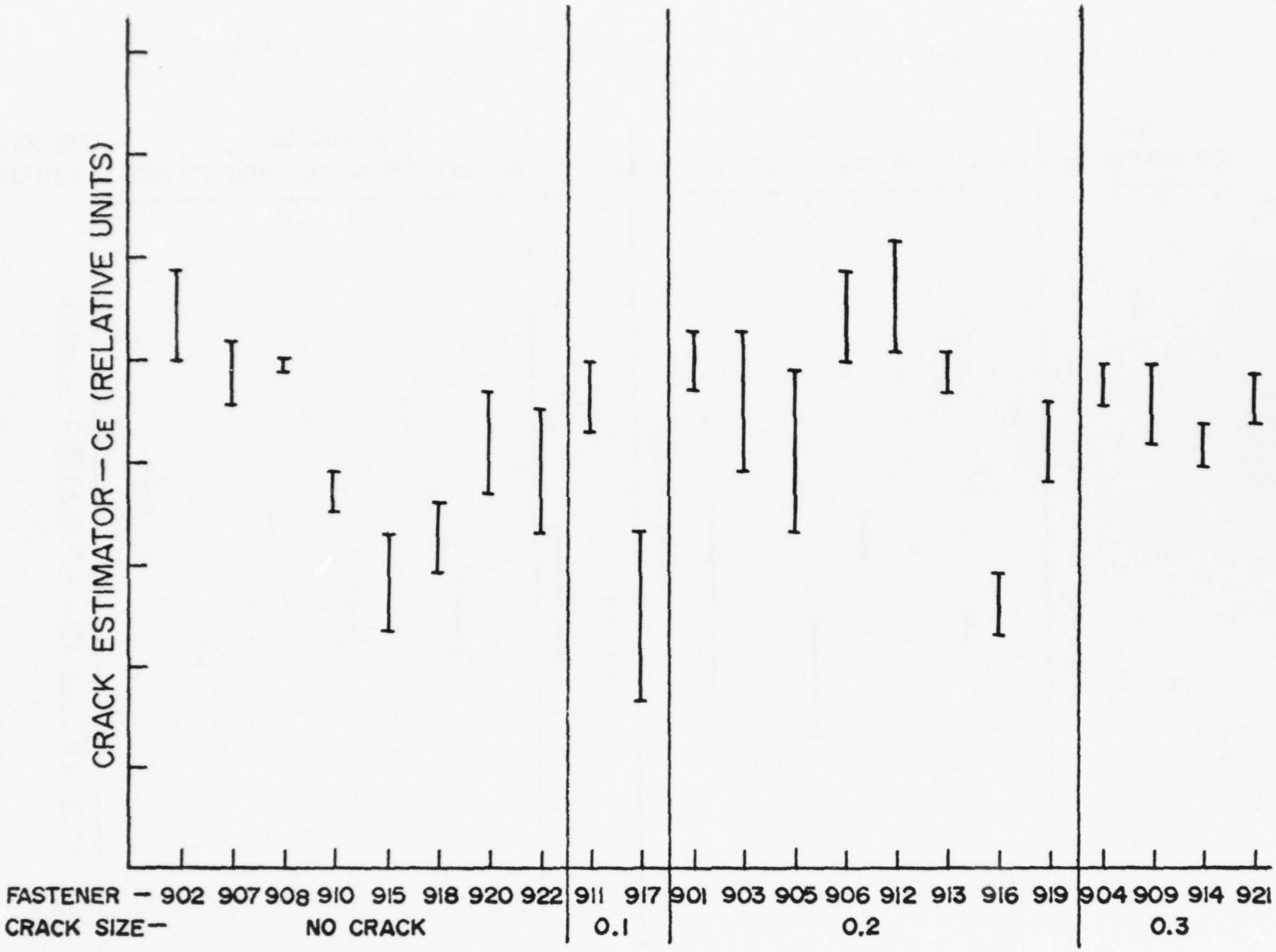


FIGURE 15. CRACK ESTIMATOR VS CRACK SIZE - SINGLE FREQUENCY (5000 HZ) (THE RANGE OF VALUES INDICATES THE SPREAD OBTAINED FROM FIVE INDEPENDENT SAMPLES)

SECTION V

FIELD EVALUATION

The MFEC system was transported to the Lockheed Georgia Company in mid-July to make the system available for field evaluation within task 8 of Lockheed's SIEP program. As a part of this program the fasteners in one wing of a C-5A, Plane 214, was to be nondestructively tested using available NDT methods. Destructive tests would be conducted later at selected locations to evaluate performance of the NDT tests. Although the MFEC system was still in the development stage, it was desirable to obtain some field experience using the system to gain better insights to guide its future development.

The field tests had to be conducted with two major limitations:

(1) Testing parameters and decision algorithms had been developed for only a limited range of test piece geometry, essentially 1/4-inch diameter, flat head double row titanium fasteners in joints having two equal 1/4-inch thick layers.

(2) Coil positioning (centering on fastener) had to be done using a laborious method of preplacing centering templates on the fasteners to be tested.

It had been intended to develop parameters for thinner joints, e.g., two-0.2 inch thick layers fastened with single row of 1/4-inch diameter, flathead titanium fasteners, however, it was found that the geometry change from double row to single row fastened joints significantly changed the metal path available for the eddy current flow and these joints could not be tested using the coil design used for the double row fastened joints. This was discovered too late in the program to permit corrections to be made.

Thickness changes at rib stiffeners in the double-row fastened joints also could not be tested. This thickness change always produced a defect indication from the system. Although the test panels used to train the system had these thickened areas, simulated cracks had been placed in the holes in these areas. Thus the system was trained to read the eddy current signals from the thickened sections as defective.

1. FIELD RESULTS

Despite these limitations useful results were obtained from the field trials. The system was brought to Lockheed by two Battelle project personnel. In a period of two days, Lockheed personel was instructed in the basics of multiple frequency eddy current technology, the fundamentals of the equipment design and operation and use of the system for the inspection of the C-5A wing joints.

These personnel operated the system competently. When minor equipment problems arose with the coil they traced the problem to its origin and made corrections.

Approximately 400 holes were inspected. Without the destructive tests no conclusions can be drawn regarding the accuracy of the tests made. One suspect fastener hole was identified which we were told was confirmed using another NDE method.

A. Effect of Ambient Temperature. The effects of ambient temperature changes were more severe than had originally been thought, and this was quickly pointed out in the preliminary evaluations of the MFEC system by BCL personnel after delivering the system to Lockheed. The following corrective action was taken.

First, we began to balance the test probe while it was suspended far away from any metal objects; six inches proved to be more than sufficient. Second, we began to use a feature of the ACQUIR program, not previously considered necessary, which was taking a compensation reading immediately after taking a reading on a fastener. This second reading measured the drift in the coil alone, which was then subtracted from the fastener reading to compensate for the drift. This compensation reading was possible only because we were using a differential probe which greatly suppressed lift off effects. The net effect was that all data taken on the fasteners was referenced to a common point, i.e., the coil output at infinite liftoff.

SECTION VI

CONCLUSIONS

(1) The prototype MFEC system, designed and built during this Phase II effort operated satisfactorily in both laboratory evaluations and field trials at Lockheed, Georgia. Minor deficiencies noted in design/fabrication were easily corrected during the field evaluation. Training of operators at Lockheed was readily accomplished and these operators performed the test on the C-5A wing competantly without assistance from Battelle project personnel.

(2) The procedure developed for testing the 1/2-inch thick, two-layer wing splice joints with double rows of 1/4-inch diameter flat head titanium fasteners appears to be satisfactory. Sawcuts simulating 0.1-inch corner cracks at the faying surface in the top of the second layer of the laboratory test panel can be detected using the multiple-frequency decision algorithm.

(3) Use of a combination of four frequencies was shown to be a definite advantage over the use of any one of these frequencies alone. The use of the multiple frequency decision algorithm instead of a single frequency voltage reading significantly increases signal separation between defective and non-defective fastener holes.

(4) The developed procedure is very sensitive to thickness and shape changes in the test piece. Thickened rib stiffener areas on the back of the joint are read as defect indications. Changes from a double row to a single row of fasteners, with the resulting change in overlap width, could not be accommodated using the same inspection probe used for double row fastened joints.

SECTION VII

RECOMMENDATIONS

Based upon the results obtained from the MFEC tests of the 1/2-inch thick, double-row titanium-fastener joints, the eddy current method of NDE appears to provide adequate defect sensitivity to cracks under installed fasteners. Development of the method should be continued. The MFEC procedure, in its present state of development, involves a learning approach in which the system is "trained" on standard panels having known cracks of various sizes as well as all other variables which can affect eddy current signals. This is a passive approach from the operator viewpoint; he merely places the coil in position and presses a button.

Experience indicates the procedure may be overly sensitive to minor variations in thickness of the test piece and shape of the joint. The latter problem can probably be corrected by changing coil configuration in the test probe. To accommodate the former limitations, however, will require having a large number of standard test pieces representing a large variety of joints. Based on the difficulty in obtaining such samples thus far in this program, this approach cannot be recommended.

For this reason, as well as others that became apparent in observing the field trials, (e.g., continuance of testing when a coil had been damaged and was malfunctioning) a different approach is recommended. The procedure should be modified to provide an opportunity for the operator to directly observe the test results as he moves the eddy current probe and makes input to the testing parameters and data interpretation. This might involve a "search" technique in which the operator places the probe on the part, centers it based on reading a signal display, eliminates unwanted variables such as lift off by phase rotation, verifies thickness of joint by taking independent thickness related readings, chooses decision function and compares defective and nondefective regions to make a crack/no crack decision.

APPENDIX

EVALUATION OF SIDE COIL FOR MULTIPLE FREQUENCY EDDY CURRENT TESTING CRACKS UNDER FASTNERS

FINAL REPORT

on

EVALUATION OF SIDE COIL FOR MULTIPLE FREQUENCY EDDY CURRENT TESTING CRACKS UNDER FASTENERS

to

UNIVERSITY OF DAYTON
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

May 20, 1977

by

Robert P. Meister

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

FINAL REPORT

on

EVALUATION OF SIDE COIL FOR MULTIPLE FREQUENCY EDDY CURRENT TESTING CRACKS UNDER FASTENERS

by

Robert P. Meister

Background

During the recently completed Phase I study conducted for Air Force Materials Laboratory, Contract No. F33615-76-C-5062 a digital MFEC system developed at Battelle's Columbus Laboratories was evaluated for detection of cracks under installed fasteners in a typical C-5A wing splice joint. A major conclusion from that study was the digital MFEC has the potential for detecting 0.3-inch and 0.1-inch cracks under titanium and steel fasteners respectively in the bottom layer of two-layer aluminum joints 3/8 to 1/2 inch total thickness. Although the sensitivity to cracks under steel fasteners was satisfactory, the sensitivity to cracks under titanium fasteners was not satisfactory. The Air Force would like to detect cracks 0.1 inch long and smaller if possible. This would greatly facilitate repair of the fastener hole by drilling it oversize and installing a larger diameter fastener.

In the first study, a cup-core eddy current coil which inspects the full circumference of the fastener hole was used. In preliminary studies prior to that program, the cup core coil showed sufficient promise of providing desired crack sensitivity to warrant further evaluation. It was considered least sensitive to positioning variables and provided a fairly simple approach to automating coil centering electrically using high frequency eddy current signal outputs.

Two alternative coil designs were considered which inspect a segment of the circumference. The idea of rotating these coils to inspect the full circumference as with the cup core coil was considered, however, it was found that adjacent fasteners and the edge of the joint produced large signal variation. Since it was most desirable to inspect the full circumference, and the cup coil had a number of desirable geometrical properties

which should enhance ease of operation, it was selected for study and proved quite successful for steel fastener joints.

Upon review of the Phase 1 program, it was decided, that a major improvement was needed to enhance sensitivity to cracks around titanium fasteners. The observation had been made that cracks around fasteners almost always initiate on the side of the fastener nearest the edge of the joint and propagate toward the joint edge. Generally, at some later time a crack will initiate on the opposite side of the fastener and propagate into the sheet. Based on this observation, it was decided that if higher crack sensitivity could be obtained by limiting inspection to a segment of the fastener hole circumference, the segment adjacent to the edge, this would still be a very viable inspection technique. Other segments around the fastener could be inspected using the same technique, however, several separate inspections would be necessary to inspect the full circumference of the fastener hole.

Therefore, this brief one-month study was funded to evaluate a side coil, designed to interrogate only the segment of the fastener circumference near the joint edge. The program was designed to obtain comparable data to that previously obtained with the cup-core coil so that conclusions could be made regarding defect sensitivities attainable with each.

Objective

The objective of this investigation was to obtain digital MFEC data on sample titanium fastener C-5A wing splice joints using a side coil, analyze this data using the AID analysis techniques, and compare crack sensitivities obtained with that obtained in the previous studies made using the cup-core coil.

Experimental Work

The experimental work conducted during this program consisted of the following tasks:

- Design and fabricate side coil
- Prepare test panels
- Acquire MFEC data on panels
- Analyze data using AID analysis

These tasks are discussed in the following section of this report.

Design and Fabricate Side Coil

The side coil shape and dimensions was based largely on using a commercially available ferrite pot core which was on hand. The pot core was cut up and machined to provide a ferrite side coil core illustrated in Figure A-1. Two identical coils were made, one for test and one for balance reference.

The cores were bifilar wound with 288 turns of 33 guage wire. The coil windings were positioned as closely as possible to one end of the core as shown in Figure A-1 while maintaining a 0.010 inch recess of the coil windings below the pole faces for fastener head clearance. For expediency, the coils were not potted or canned, but used in the as-wound-condition as shown in Figure A-1.

Preparation of Test Panels

The same two titanium fastened test panels, Nos. 1-3 and 1-4, used in the previous investigation were used for this study. An additional section of this panel geometry containing 28 fasteners in two rows, designated 1-7 was used primarily to provide a reference fastener for balancing. A sketch of the cross section of the test panel is shown in Figure A-1. Only the fastener row indicated in Figure A-1 was tested i.e., the row closest to the joint edge in the bottom layer.

The test panels were disassembled and notches simulating cracks were cut using a jeweler's saw in the same manner as in the previous program. Saw cuts were made to simulate 0.1, 0.2, and 0.3 inch long cracks at the faying surface of the bottom layer. In all cases the "crack" length is measured from the fastener hole on the faying surface and the "crack" front

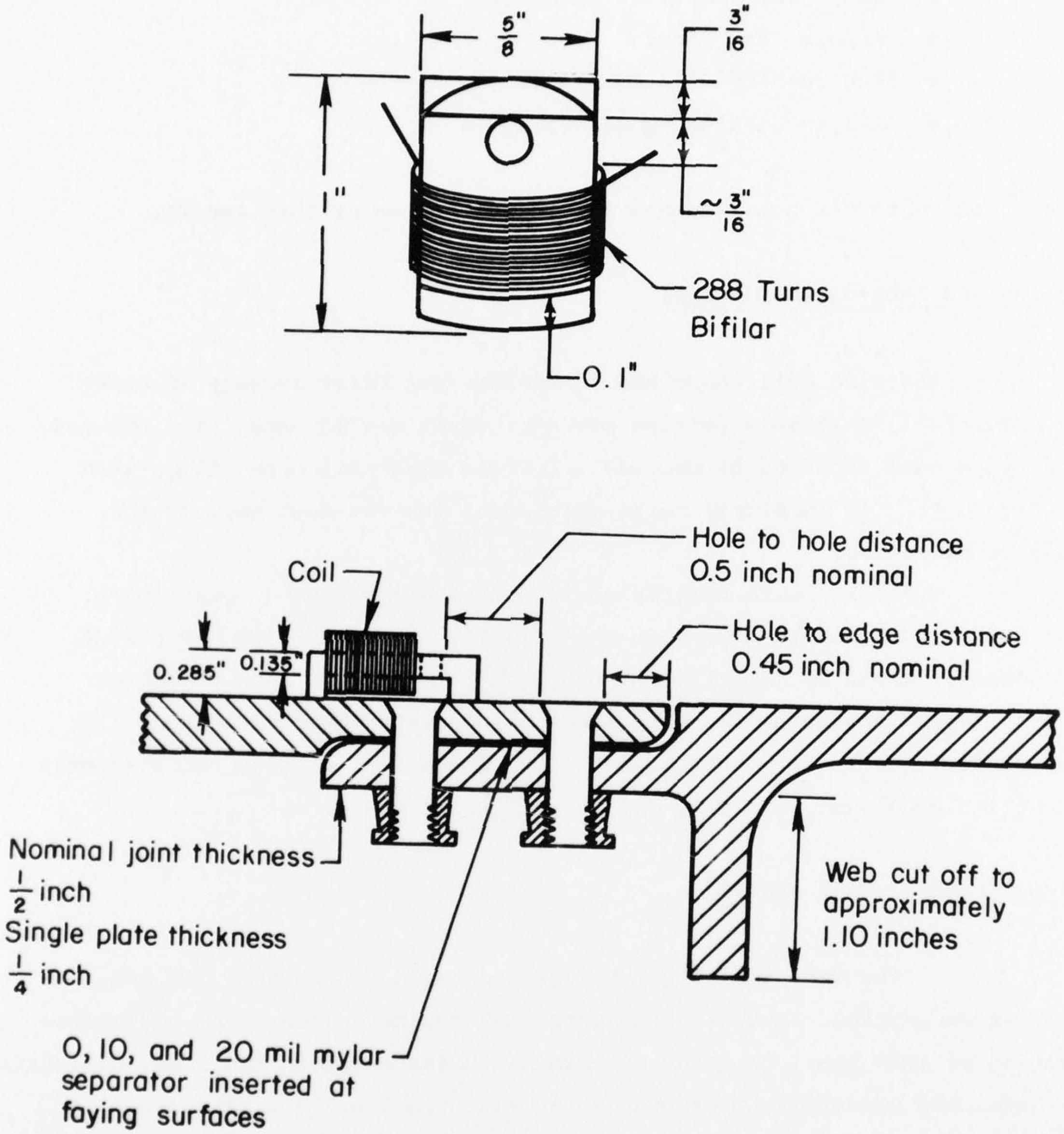


FIGURE A-1. BOTTOM VIEW OF SIDE COIL (TOP) AND SIDE VIEW OF SIDE COIL (BOTTOM) IN POSITION FOR TESTING FASTENER

to the faying surface is 45, 67.5, and 90 degrees for the 0.1, 0.2, and 0.3 inch "cracks" respectively. Notches were machined in fastener holes which had not been notched in the previous program or had only small notches in the top layer. A number of holes were left unnotched to represent a "no-crack" condition.

The panels were reassembled with 0.01 or 0.02 inch thick Mylar sheets between the top and bottom layers along approximately one third of the panel length to simulate sealant and varying sheet separation.

The total number of fastener holes tested for each test condition and the total number of tests is listed below:

Condition	No. of Fastener Holes	No. of Tests
No Crack	15	72
0.1" Crack	7	35
0.2" Crack	12	60
0.3" Crack	4	20
	Total	187

Testing Procedure

Each fastener hole, except three no crack holes, was tested five times to obtain sufficient data for statistical analysis. All fasteners were tested once sequentially starting at one end of the panel and proceeding to the opposite end. This procedure was then repeated until five tests had been made on all the fasteners. The last test on each of the last three no-crack fasteners in the sequence was not made due to operator error. End fasteners and fasteners over stiffeners where thickness was greatly increased were not tested.

Prior to testing, the reference coil was secured over a "no-crack" fastener in Panel 1-7. The system was then balanced to less than 0.010 volts. The test coil was then positioned over the first fastener to be tested and an in-phase and quadrature reading taken at each test frequency Frequencies used were 90, 330, and 1219 Hz, the same as used the previous program. Phase angles used were 0-90, 0-90, and 45-135 for the three frequencies. Subsequent fasteners were then tested in the same manner until all tests had been made.

Analysis of Data

After taking the data, it was sorted to collect all no-crack, 0.1, 0.2, and 0.3 inch crack holes into groups and the plots shown in Figures A-2-4 showing the in-phase and quadrature voltage readings at each frequency for each fastener were produced. These plots give some indication of the detectability of the cracks using a standard single frequency eddy current technique.

In addition, the same data was put into the CDC 6400 computer and an AID analysis was made. The AID analysis was made using the same set of predictors used in the previous program. The AID tree produced is shown in Figure A-5. The classification algorithm was implemented directly on the PDP 11/40 minicomputer to make a series of binary decisions using the splitting variables indicated by AID. This program then places the results of each fastener test on a crack probability scale of 0 to 1 which is displayed on the graphics terminal as illustrated by Figure A-6 (top).

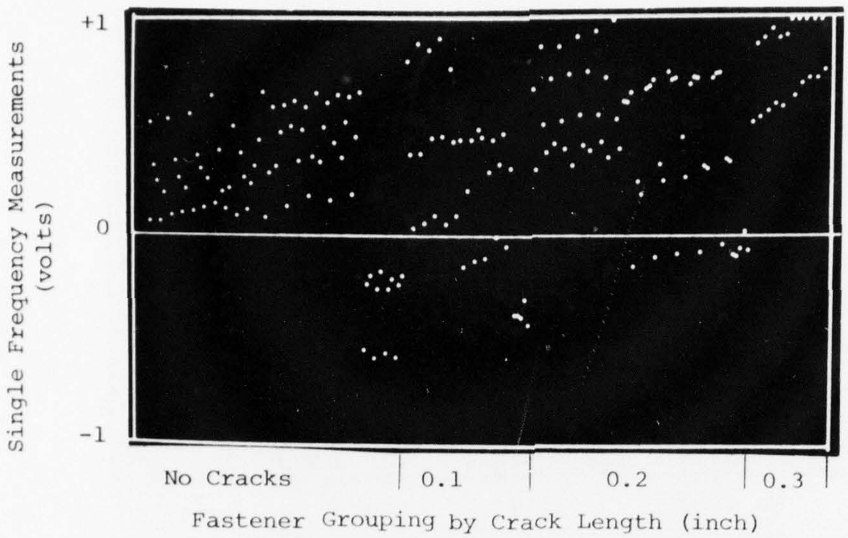
Discussion of Results

Figure A-6 showing the direct comparison of MFEC results obtained using the side coil and the cup core coil. As noted in the figure, the side coil provided significantly better sensitivity to all crack sizes with less Type 2 errors, i.e., calling an uncracked hole as being cracked.

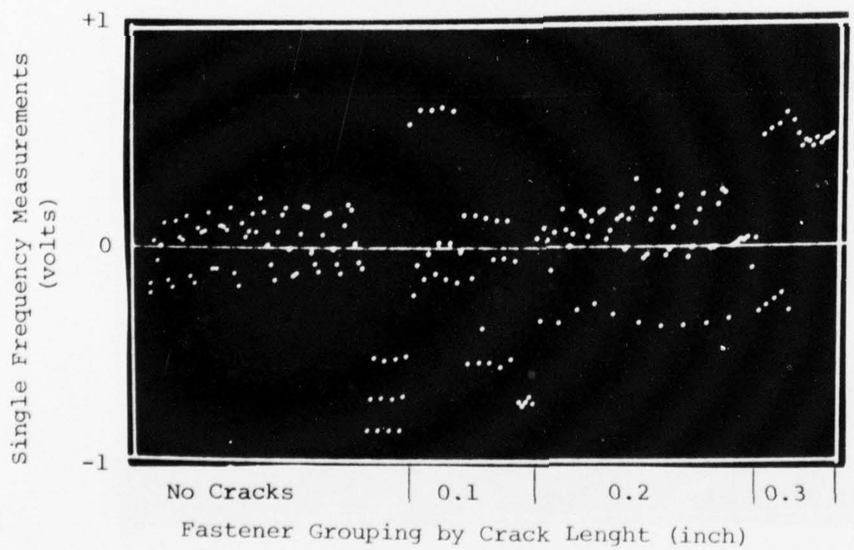
Results obtained with the side coil are listed below:

Condition	Total Number Possible	Correct Calls
No Crack	72	67
0.1" Crack	35	32
0.2" Crack	60	58
0.3" Crack	20	20

A total of 110 out of 115 cracked holes were correctly classified and 67 of 72 no-crack holes were correctly classified. The AID analysis failed to classify five cracked and five no-crack holes.

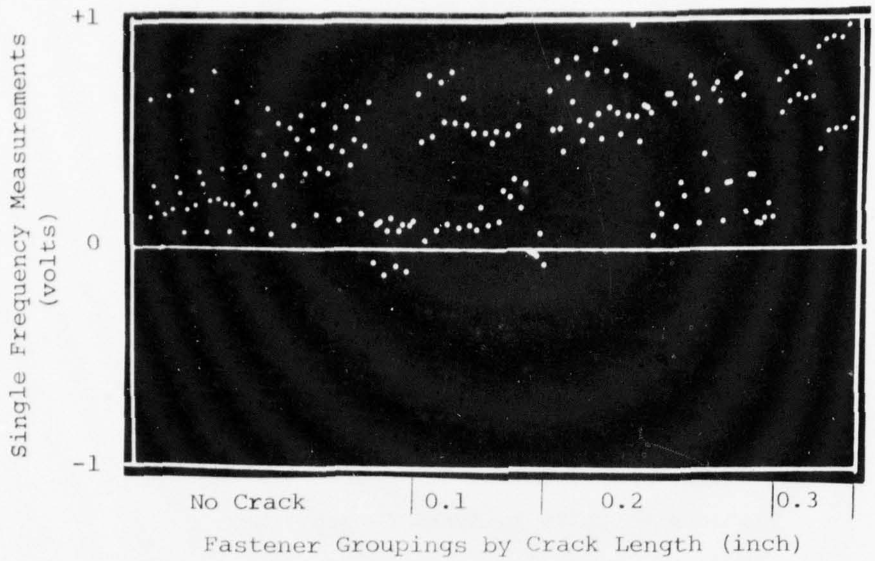


a - Inphase

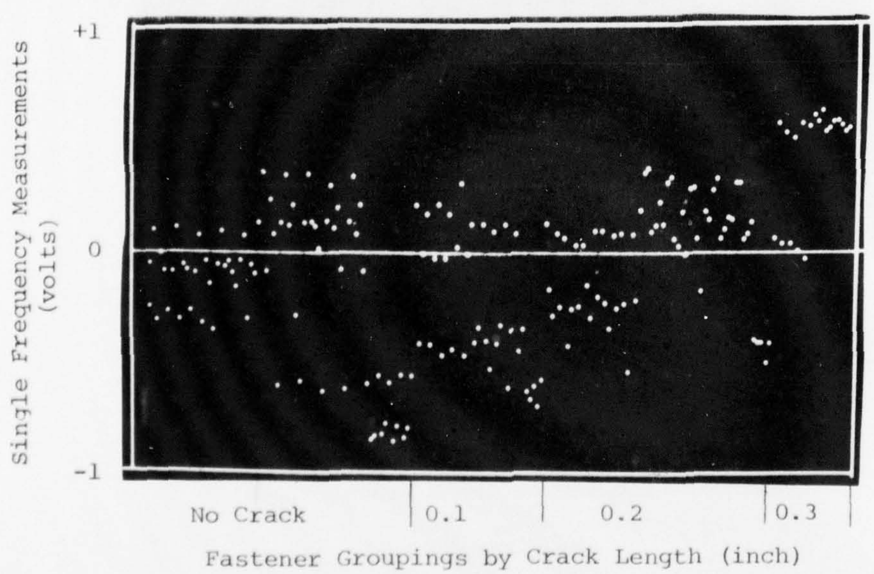


b- Quadrature

FIGURE A-2. SINGLE FREQUENCY MEASUREMENTS FOR MFEC ANALYSIS ON TITANIUM FASTENERS — 90 Hz

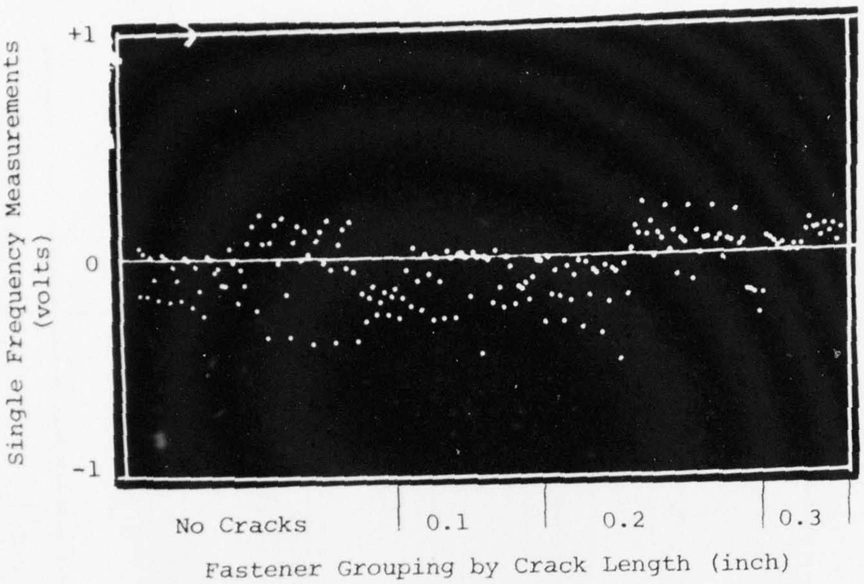


a - Inphase

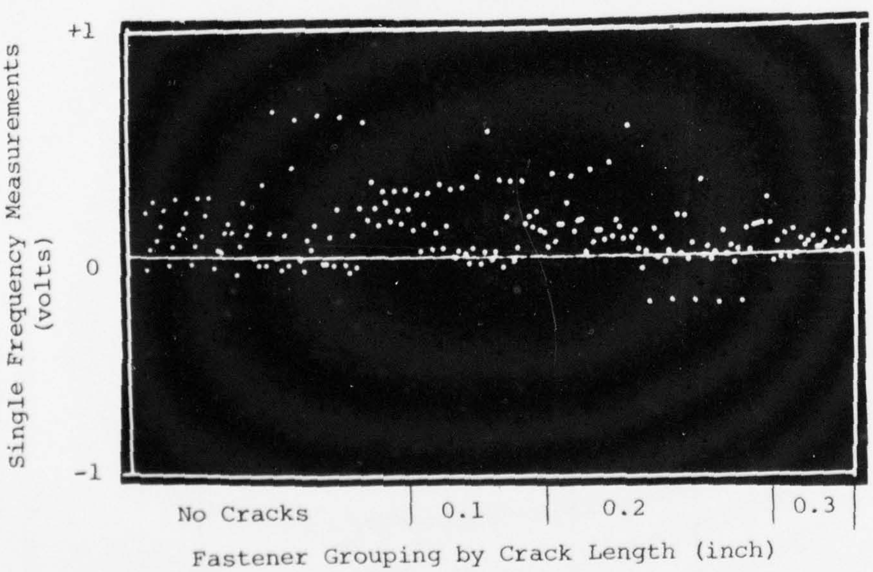


b - Quadrature

FIGURE A-3. SINGLE FREQUENCY MEASUREMENTS FOR MFEC ANALYSIS ON TITANIUM FASTENERS — 330 Hz

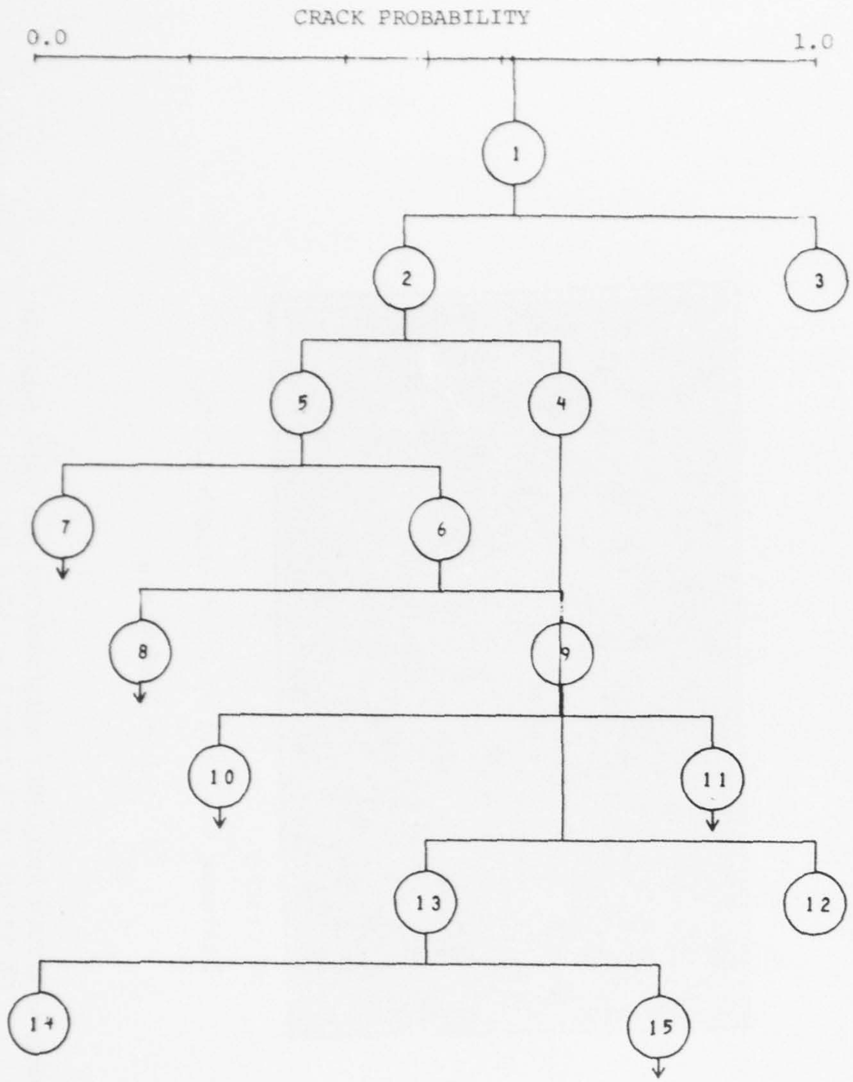


a - Inphase



b - Quadrature

FIGURE A-4. SINGLE FREQUENCY MEASUREMENTS FOR MFEC ANALYSIS ON TITANIUM FASTENERS — 1219 Hz

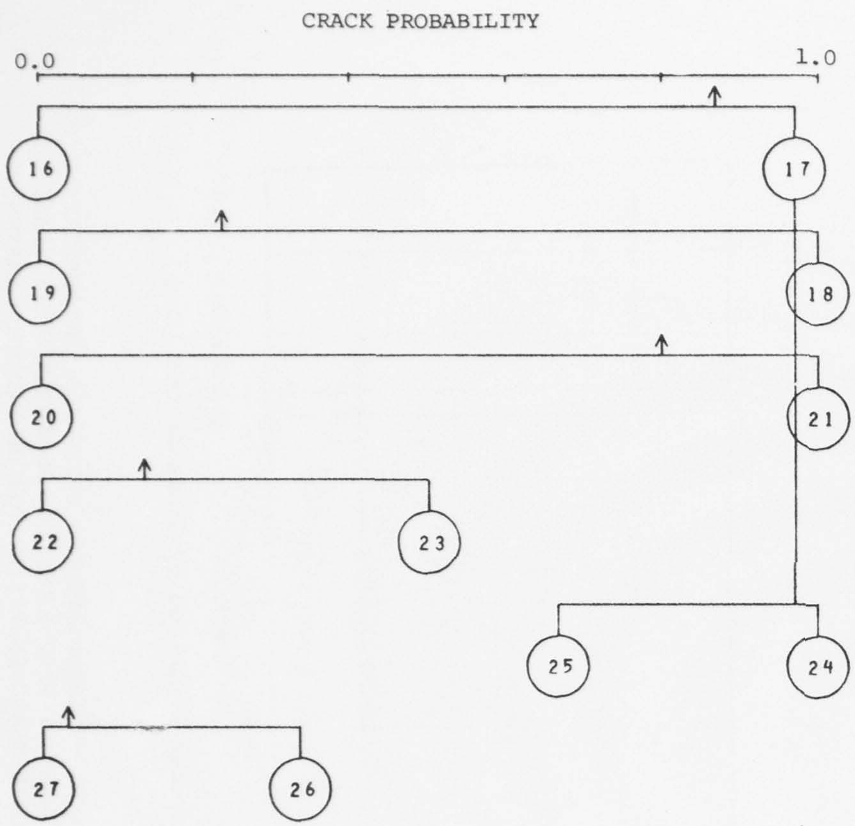


SUMMARY TABLE

---TOTAL GROUP---	
CRITERION -CRACK TOTAL GROUP N = 187 MEAN = 38.74 STD. DEV. = 30.66	
PARENT 1 SPLITTING VARIABLE - X59	
MEAN= 29.89 S.D.= 31.46 N= 137	MEAN= 63.00 S.D.= .00 N= 50
PARENT 2 SPLITTING VARIABLE - X37	
MEAN= 21.51 S.D.= 29.07 N= 82	MEAN= 42.38 S.D.= 29.56 N= 55
PARENT 5 SPLITTING VARIABLE - X30	
MEAN= 2.10 S.D.= 11.51 N= 30	MEAN= 32.71 S.D.= 31.98 N= 52
PARENT 6 SPLITTING VARIABLE - VE2(90)	
MEAN= 8.40 S.D.= 21.92 N= 15	MEAN= 42.57 S.D.= 29.99 N= 37
PARENT 4 SPLITTING VARIABLE - X22	
MEAN= 14.02 S.D.= 26.72 N= 17	MEAN= 54.71 S.D.= 21.30 N= 38
PARENT 9 SPLITTING VARIABLE - X20	
MEAN= 31.50 S.D.= 31.50 N= 24	MEAN= 63.00 S.D.= .00 N= 13
PARENT 13 SPLITTING VARIABLE - X30	
MEAN= .00 S.D.= .00 N= 9	MEAN= 50.40 S.D.= 25.20 N= 15

FIGURE A-5. AID ANALYSIS OF DATA TAKEN ON TITANIUM FASTENERS HAVING 0.1, 0.2, AND 0.3 INCH CRACKS USING SIDE COIL

DEPENDENT VARIABLE = CRACK PROBABILITY



SUMMARY CONTINUED	
PARENT 11 SPLITTING VARIABLE - X106	
MEAN= .00 S.D.= .00 N= 9	MEAN= 61.15 S.D.= 10.69 N= 39
PARENT 10 SPLITTING VARIABLE - X100	
MEAN= .00 S.D.= .00 N= 13	MEAN= 63.00 S.D.= .00 N= 9
PARENT 15 SPLITTING VARIABLE - X100	
MEAN= .00 S.D.= .00 N= 3	MEAN= 63.00 S.D.= .00 N= 12
PARENT 8 SPLITTING VARIABLE - X82	
MEAN= .00 S.D.= .00 N= 11	MEAN= 31.50 S.D.= 31.50 N= 9
PARENT 17 SPLITTING VARIABLE - X100	
MEAN= 92.00 S.D.= 29.70 N= 3	MEAN= 63.00 S.D.= .00 N= 31
PARENT 7 SPLITTING VARIABLE - X105	
MEAN= .00 S.D.= .00 N= 27	MEAN= 21.00 S.D.= 29.70 N= 3

FIGURE A-5 (Continued)

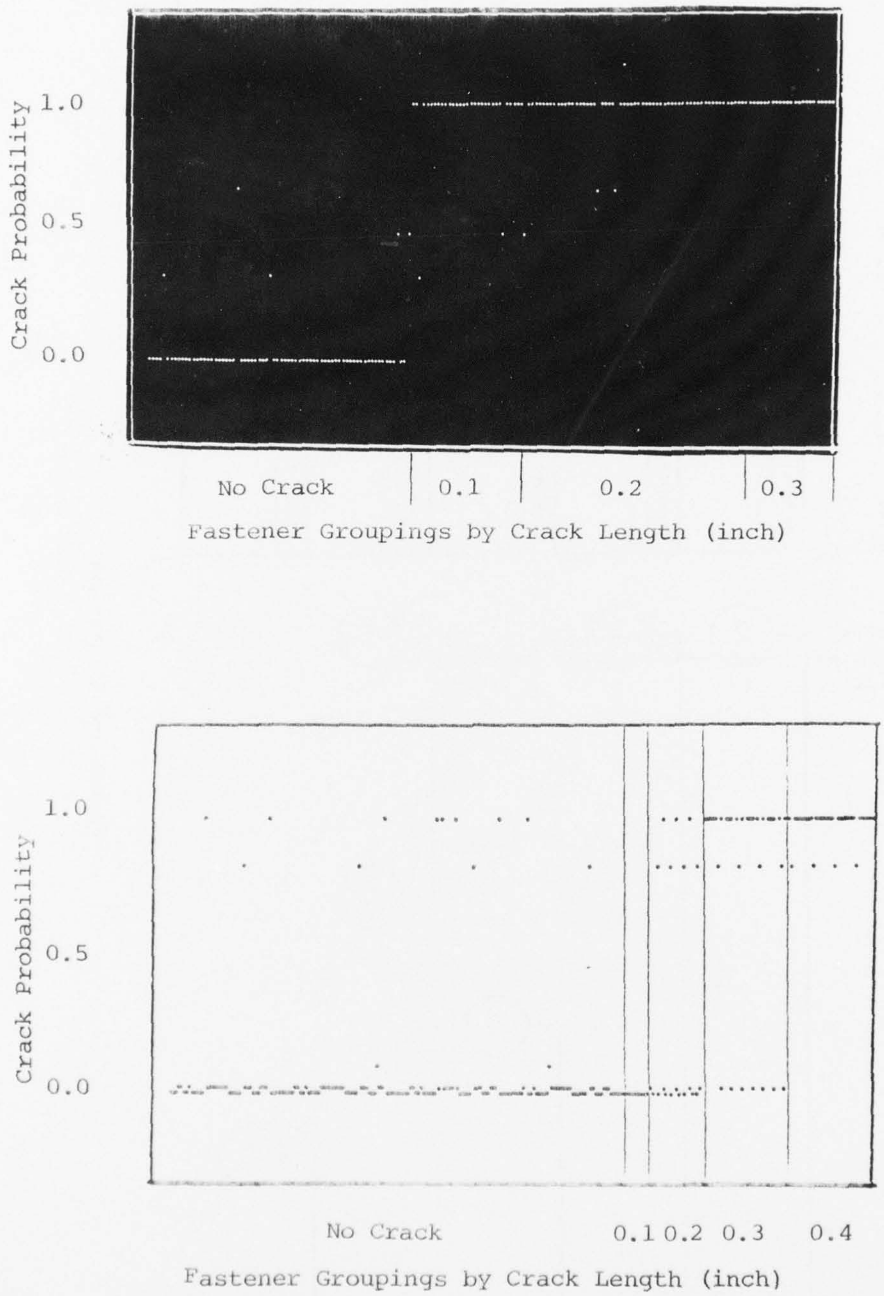


FIGURE A-6. MFEC DECISION PROCESS USING AID IMPLEMENTATION TO CLASSIFY MFEC SIDE COIL MEASUREMENTS(TOP) AND CUP COIL MEASUREMENTS(BOTTOM) ON TITANIUM FASTENERS

As noted in the AID tree, Figure A-5, the holes not correctly classified are left in parent groups near the center of the crack probability scale. In an actual inspection, the decision algorithm would have placed these holes in the cracked or uncracked class if a particular threshold value of the predictor variable had been chosen to made the decision. However, in future studies, to increase the test reliability, we should investigate the possibility of re-examining all holes haveing crack probability of >.10 and <.90, for example with a second decision process and separately classifying them into crack versus no-crack categories.

The AID tree developed in this program is not as short as desired, requiring about five or six splits to put all fasteners into terminal groups. There are two possible reasons for this. During initial testing we discovered a defective IC in the interface electronics and to meet schedule had to use a replacement operational amplifier which was not as stable as desired. Also, since the coils were used in the as-wound condition, the test was subject to more variation due to operator handling, e.g., temperature variation, differences in placement pressure, etc. Many of the splits involve predictor variables designed to normalize the signals to reduce the effect of noise. It is very encouraging that the AID analysis could be so effective in spite of the noise variations. This is evidenced graphically by comparison of the single frequency readings, Figures A-2-4, with the MFEC results in Figure A-6 (top).

It is also encouraging that all cracks were separated using only three predictor variables, the most powerful being one that was used to classify steel fasteners in the previous program. The total of ten misses occurred on eight fastener holes. The five no-crack misses occurred on four holes with one of the holes being misclassified two out of five tests and the other misses in one out of five tests. Similarly, the five crack misses occurred on four holes with one of the holes having a 0.2 inch crack being misclassified twice. These results indicate if repetitive tests were made, the reliability could be outstanding!

Conclusions

Use of a side coil, inspecting one segment of the fastener hole, provides greatly improved crack sensitivity over cup core coil, full hole circumference tests for cracks around titanium fasteners. The side coil offers excellent potential for developing a technique to detect 0.1 inch cracks in the second layer of 0.5 inch thick joints.

Recommendations

1. The side coil design should be adopted in lieu of the cup core for use in the prototype digital MFEC system currently being built for AFML.
2. Further studies should be conducted to optimize the side coil design, define its limitations in crack sensitivity and develop decision algorithms for use on the various critical fastener groups in the C-5A aircraft.
3. Studies should be conducted toward optimizing test reliability through either (a) reprocessing data on holes which are not strongly classified as cracked or not cracked with a second decision algorithm or (b) performing repeated tests on the same fastener.

/je

☆U.S.Government Printing Office: 1979 — 657-002/688